AAVSO Spectroscopy: Project Miras

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1 Mira stars

Miras (from the proto-type *o* Cet or *Mira*) are radially pulsating stars that have always been favorite targets for amateurs for a number of reasons: hugely bright, large amplitude, easily manageable long periods, unpredictable variability from one cycle to the next, etc.

The Mira instability strip is located at the upper right corner of the HR diagram (were the largest and coolest stars are located), and it is crossed by stars ascending the giant branch for the second and last time in their life, on the way to blow out into the interstellar space their outer layers and turn into the nuclei of Planetary Nebulae at first, and then white dwarfs.

The internal structure of a Mira sees an inert, electron-degenerate central core (the future white dwarf), surrounded by two burning shells and an outer envelope (where pulsations occur). In the innermost shell, Helium is burned into Oxygen and Carbon, which accumulate as ashes onto the central core that grows in mass aiming to reach that appropriate for a white dwarf. In the outermost of the two burning shell, Hydrogen is turned into Helium. These two shells undergo on/off transitions (with time scales of a thousand years) that allow the convection (through the so-called 3^{rd} *dredge-up* process) to bring at the surface material heavily contaminated by the nuclear burning in the two shells below; in particular, Carbon and the so-called $s-$elements (Y, Zr, Mo, Ba, La, Ce, Nd, Sm).

The increasing pollution of the outer layers of a star by $s-$elements and Carbon, dredged-up from the interior, causes a gradual transition of the spectral type from the initial M (dominated by absorption bands from TiO molecules), to S-type (strong absorption bands from molecules involving $s-$elements appear besides TiO, in particular ZrO), to Carbon type (molecules involving Oxygen disappear from optical spectra, to be replaced by molecules based on Carbon, especially C_2 and CN). Miras variables are observed in all these three flavors, being distributed among M, S and C spectral types.

2 Spectroscopy of a radially pulsating star

2.1 Radial velocity

This is something restricted to those equipped with high resolution spectrographs (Echelle or able to provide a dispersion of 0.2 Å/pix or better[1]

A radially pulsating star has a "breathing" outer radius, half of the time expanding and the rest contracting backward. Such a rhythmic motion causes its spectrum to oscillate in phase, between blue-shifted (when the atmosphere expands) and red-shifted (when it contracts back) conditions.

By measuring its radial velocity along the pulsation cycle, we can follow the "breathing" of the atmosphere of a Mira variable. We may expect a total amplitude of the radial velocity change of the order of 20 km/sec, which translates into 0.4 Å at red wavelengths (6000 Å). This is easily well within the measurement capabilities of high-resolution spectrographs in amateurs' hands: if wisely and correctly used, they can deliver true accuracies of 1-2 km/sec on a single spectrum.

2.2 Surface temperature

Let's focus on Miras of the M spectral type, the most numerous ones and those dominated by TiO molecular bands. The depth of TiO is a strong function of temperature, in addition to electron density and other effects. It is possible to follow the change in surface temperature along a pulsation cycle by measuring the parallel

[1]How to derive your dispersion scale ? If your CCD has 2000 pixels and your recorded spectrum covers 500 Å, the dispersion scale is 0.25 Å/pix. What about the resolving power ? If an intrinsically narrow line (like an isolated one in the comparison spectrum) has a FWHM of 3 pixels than, in the present example, its FWHM in Å is 3×0.25=0.75 Å. The resolving power is expressed as $\lambda/\Delta\lambda$, so observing at Hδ (=4101 Å) a FWHM=0.75 Å corresponds to a resolving power 5500, and 8750 at Hα (=6563 Å).

change in the depth of the TiO bands, from hottest temperatures (when the TiO bands are the shallowest) to the coolest ones (when the TiO bands are the strongest and deepest).

2.3 Shocks in a pulsating atmosphere

There is a lot of upward and downward movement in a radially pulsating atmosphere as that of a Mira. Material infalling from the previous cycle can slam against that expanding from the next cycle, causing a shock front. At a shock front, Hydrogen (and other elements) can be ionized. When recombining with electrons, Balmer lines (Hα, Hβ, Hγ, Hδ, Hϵ, ...) are emitted. Depending from the optical thickness of the outer atmospheric layers they have to cross, these emission lines can be seen in the spectra. Their shape will reflect the intimate kinematics of the shock front and of the external absorbing layers located above the shock front.

3 Goals of Project Miras

3.1 Radial velocities

3.1.1 The overall breathing

A <u>1^{st} goal</u> is to derive a detailed radial velocity curve covering the whole pulsation cycle. This will allow to investigate how the Mira pulsate with respect to its lightcurve (for ex.: does it expand (blue-shifted) during the rise to or the decline from maximum brightness ?)

We know that the lightcurve of a Mira seldom replicates itself, with large excursion either in the brightness of minima and maxima as well as some variability of the pulsation period around a mean value. A <u>2^{nd} goal</u> would then be to see if and how these lightcurve changes reverberates into equivalent changes in the radial velocity curves.

A further <u>3^{rd} goal</u> follows naturally. The shape of the lightcurve tend to change with the pulsation period: is there a similar trend in the shape of the radial velocity curve with the pulsation period ?

A <u>4^{th} goal</u> could be to compare the radial velocity curves of Miras of the M, S and C spectral types: have their similar shapes ?, do they behave the same way compared to the respective lightcurves ?, and what about the full amplitude of the pulsation, is it function of the spectral type of the Mira ?

3.1.2 The differential breathing

There is a more challenging, but also more intriguing, application of radial velocities to the pulsation of a Mira.

Let's start from a simple spectroscopic notion: the stronger a spectral feature is, the more external are the atmospheric layers where it forms (basically, a stronger line or band needs less atoms or molecules along the line of sight to block the view of more internal regions; that's equivalent to say that the line of sight can penetrate deeper into the atmosphere if the observing wavelength is away from the center of a strong absorption band).

Therefore, a final <u>5^{th} goal</u> to pursue would be: how a radial velocity curve obtained from measurements at the center of strong molecular bands would compare with those focusing in the region away from molecular bands ? Do we see different amplitude ? Different phases perhaps ?

3.2 Surface temperature

There is no special requirements on the spectral apparatus to be able to measure the depth of molecular bands, a task suitable even for low dispersion spectrograph. A dispersion between 2 and 6 Å/pix will do fine.

3.3 Shocks in a pulsating atmosphere

We have basically two goals here, the first good also for low resolution observations, the second reserved only for the highest resolving powers.

<u>1^{st} goal</u>: in nearly all astrophysical environments where emission lines are present (eg. planetary nebulae, novae, interacting binaries, supernova remnants, etc.), invariably Hα is stronger than Hβ, which in turn is stronger than Hγ, and so forth down to the head of the series.

Is that so for Miras too ? If not, is the deviation dependent from the pulsation phase (i.e. the situation is different at maximum brightness compared to minimum) ? Or from the length of the pulsation period (i.e. short period Miras behave differently from long period ones) ? In respect to the relative intensity of Balmer emission lines, do Miras of different spectral types M, S and C behave differently ?

<u>2^{nd} goal</u>: to follow along the pulsation cycle how the profile of an emission line change (multiple peaks, asymmetric shapes, super-imposed sharp absorption components, etc.). Hint: focus on the strongest emission line derived from the previous task.

		RA	DEC	t_o	P (days)	V_{max}	V_{min}	spectrum
R	And	00 24 01.95	+38 34 37.3	53820	409.2	5.8	15.2	S3,5e-S8,8e(M7e)
o	Cet	02 19 20.79	−02 58 39.5	44839	331.96	2.0	10.1	M5e-M9e
Y	Per	03 27 42.39	+44 10 36.5	45245	248.60	8.1	11.3	C4,3e(R4e)
R	Lep	04 59 36.35	−14 48 22.5	42506	427.07	5.5	11.7	C7,6e(N6e)
S	Cam	05 41 02.49	+68 47 55.0	55169	329.9	7.7	11.6	C7,3e(R8e)
R	Gem	07 07 21.27	+22 42 12.8	43325	369.91	6.0	14.0	S2,9e-S8,9e(Tc)
V	Cnc	08 21 42.82	+17 17 06.5	54108	269.7	7.6	13.3	S0e-S7,9e
R	Leo	09 47 33.48	+11 25 43.8	44164	309.95	4.4	11.3	M6e-M8IIIe-M9.5e
S	UMa	12 43 56.68	+61 05 35.5	45778	225.87	7.1	12.7	S0,9e-S5,9e
R	Hya	13 29 42.77	−23 16 52.7	43596	388.87	3.5	10.9	M6e-M9eS(Tc)
V	CrB	15 49 31.31	+39 34 17.9	43763	357.63	6.9	12.6	C6,2e(N2e)
V	Oph	16 26 43.71	−12 25 35.8	45071	297.21	7.3	11.6	C5,2-C7,4e(N3e)
X	Oph	18 38 21.13	+08 50 02.8	44729	328.85	5.9	9.2	M5e-M9e
R	Aql	19 06 22.25	+08 13 48.0	55337	269.84	5.3	11.9	M5e-M9IIIe
χ	Cyg	19 50 33.92	+32 54 50.6	42140	408.05	3.3	14.2	S6,2e-S10,4e(MSe)
U	Cyg	20 19 36.59	+47 53 39.1	44558	463.24	5.9	12.1	C7,2e-C9,2(Npe)
T	Cep	21 09 31.78	+68 29 27.2	44177	388.14	5.2	11.3	M5.5e-M8.8e
X	Aqr	22 18 39.33	−20 54 04.0	52951	311.4	7.2	15.0	S6,3e:(M4e-M6.5e)

4 Target selection

A list of suitable targets is proposed to pursue the above goals. They are listed in the Table, which has been compiled according to the following main criteria:

- validated Mira type of variability according to GCVS (General Catalog of Variable Stars)
- detailed spectral classification available in GCVS
- 18 targets, equally divided among M, S and C spectral types
- among the V-band brightest Miras for their respective spectral types
- well distributed in RA and all observable from +45 declination
- a fair fraction, well distributed in RA, also observable from the southern hemisphere
- one circumpolar (DEC¿60) Mira each for the M, S and C spectral types, so to quickly cover a full pulsation cycle, without annoying interference from Solar conjunction

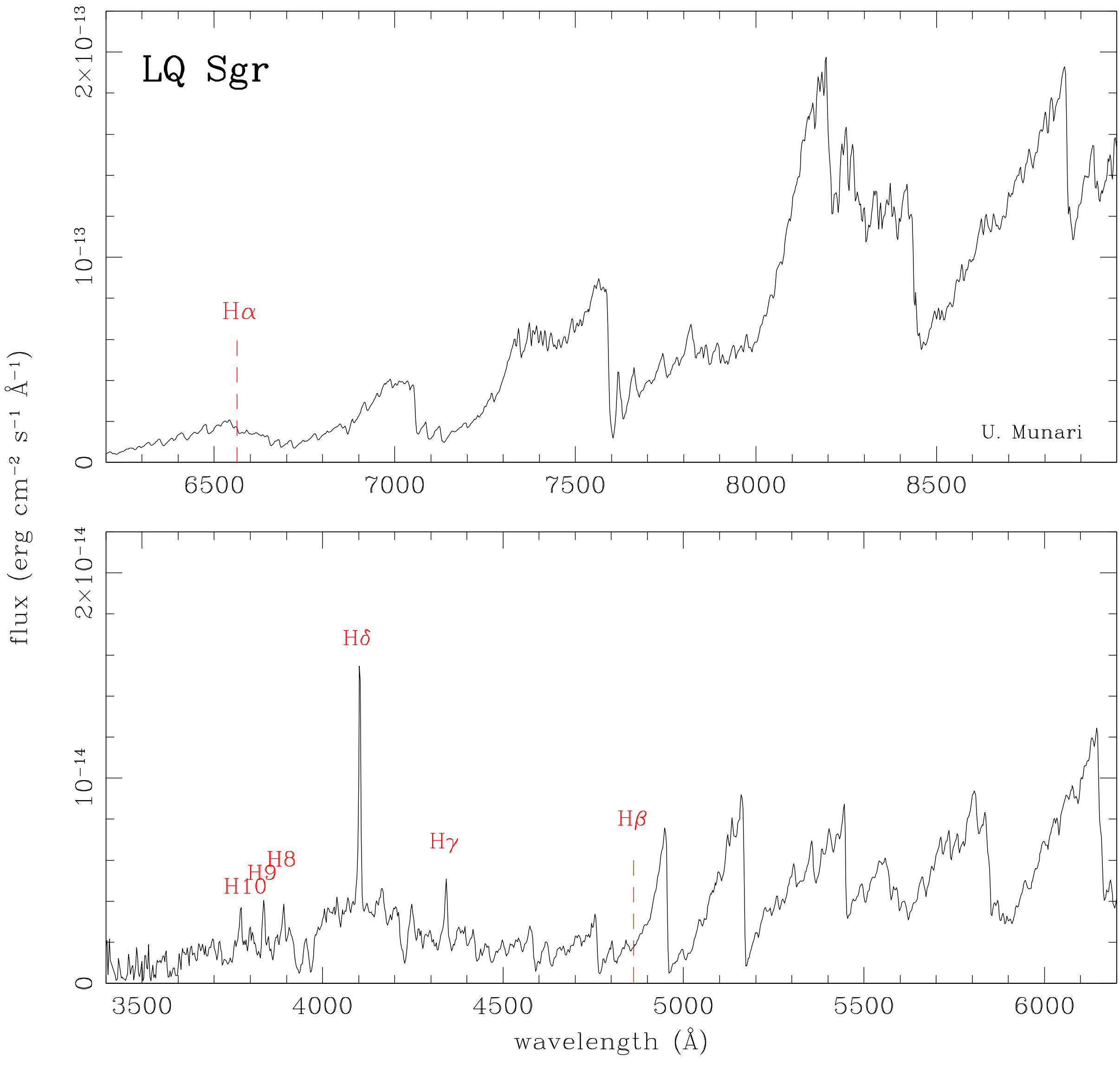

Figure 1: Low resolution spectrum (2.3 Å/pix, resolving power 1000 at Hα) of a classical Mira, to illustrate the depth of TiO molecular bands and the odd relative intensity of Balmer emission lines (dashed lines mark the position where Hα and Hβ should be). Note the ordinate scale in the two panels: that for the bluer one is 10 times expanded compared to the redder one ! Miras are so red that it is impractical to plot a spectrum in linear coordinates when covering the whole optical range. This is the reason for changing to a logarithmic scale in the remaining pictures.

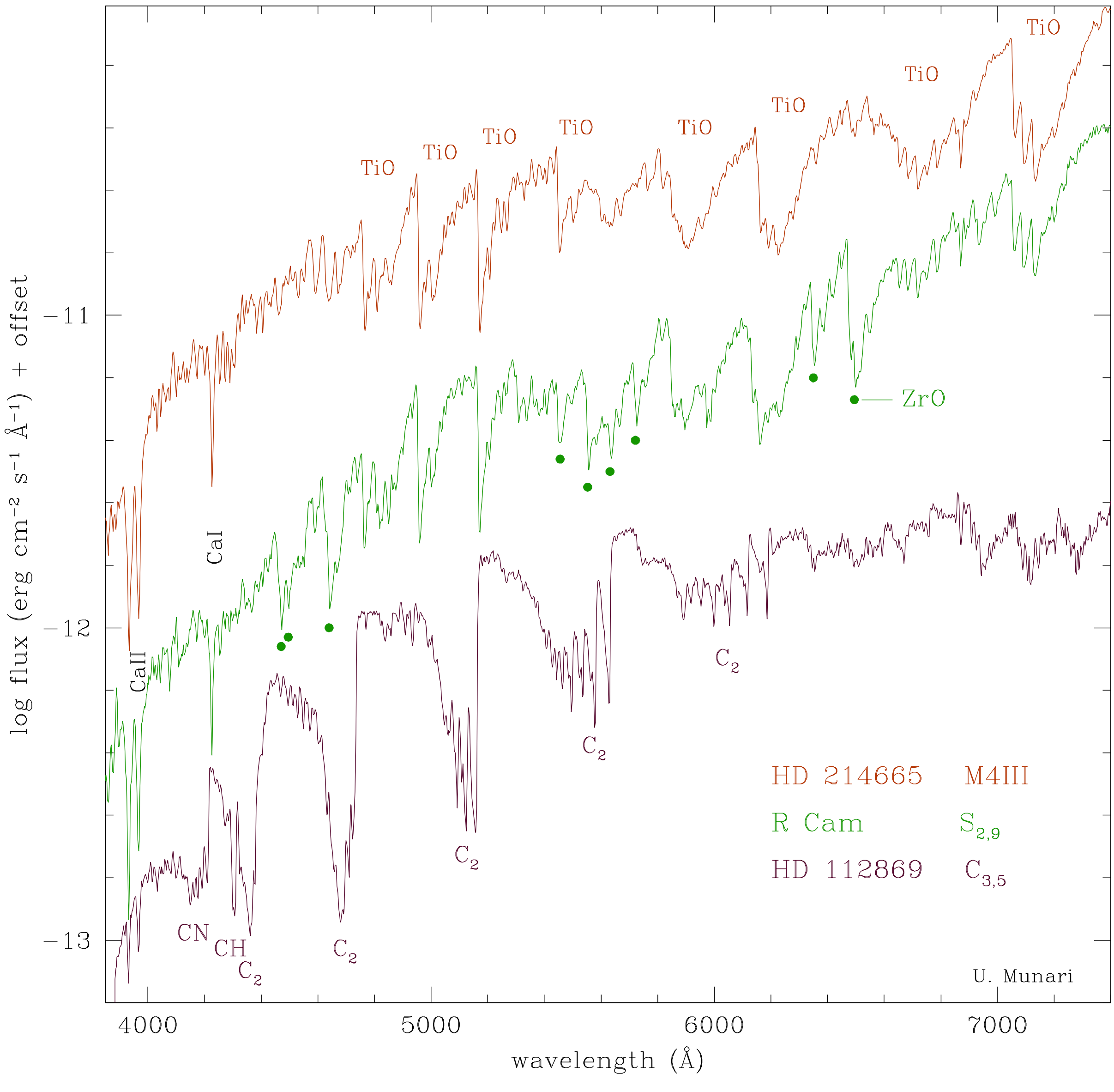

Figure 2: The low resolution spectra (2.3 Å/pix, resolving power 1450 at Hα) of three cool giants are compared to illustrate the differences between M, S and C spectral types. In M type spectra, basically all molecular absorption is due to TiO. In S type spectra, ZrO bands appears beside TiO. No metallic oxides (i.e. molecules containing Oxygen) are instead present in C type spectra, they being dominated by Carbon bearing molecules (expecially C_2 bands). Note how TiO and ZrO bands have a sharp edge to the blue and degrade toward the red, the reverse for CN and Swan C_2 bands.

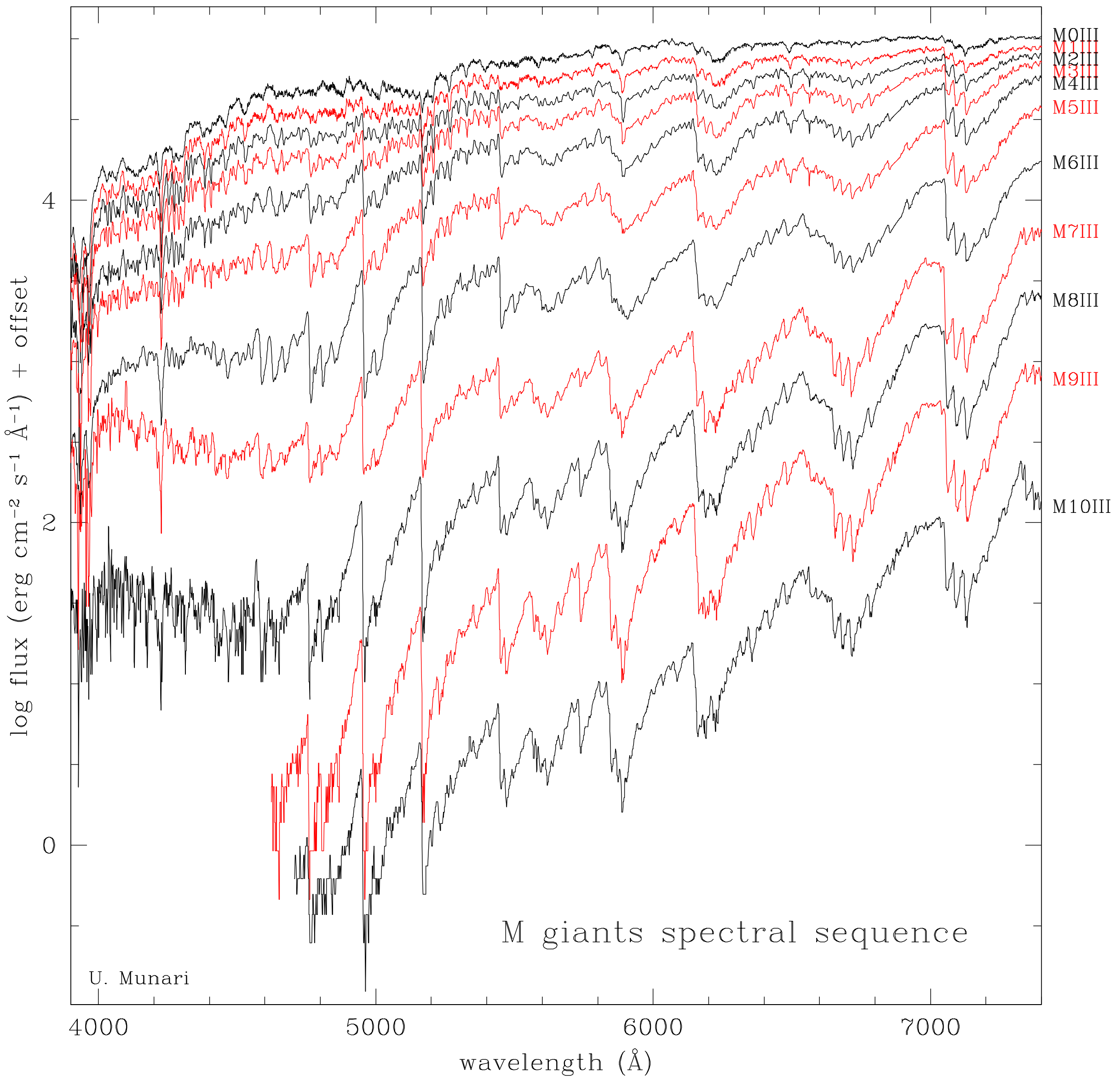

Figure 3: This sequence of low resolution (1.0 Å/pix, resolving power 3000 at Hα), reddening-free spectra of M giants (from M0III at the top, to M10III at the bottom) show how the general slope gets redder with advancing spectral type and TiO absorption bands modify their depths, mutual intensity and substructures within the bands themselves. The atmospheric temperature declines from M0 ($\sim$3900 K) to M10 ($\sim$2500 K).

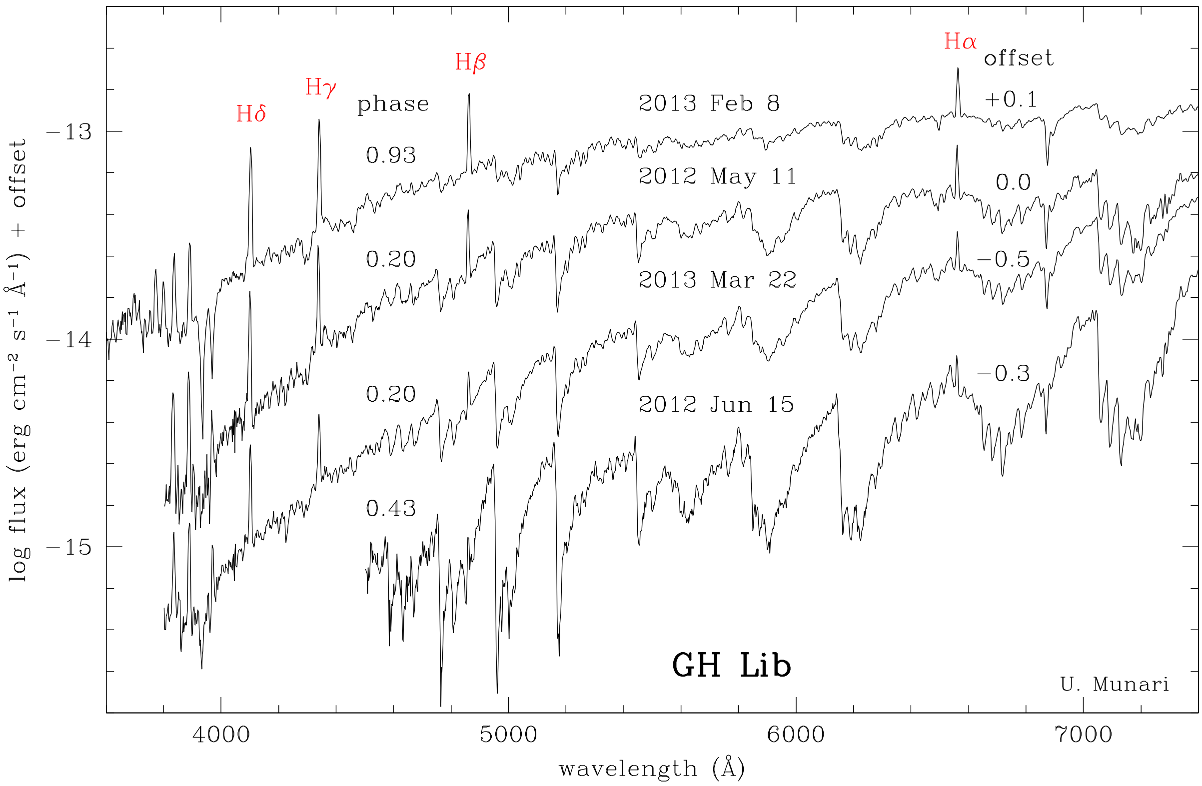

Figure 4: Change in spectral type of the M type Mira GH Gem along its pulsation cycle (∼M3III around maximum, ∼M7III at minimum; 2.3 Å/pix dispersion and 1000 resolving power at Hα). Note primarely two things about the emission lines: how their intensity vary along the pulsation cycle, and how different is the relative intensity of the Balmer lines compared to the case of LQ Sgr in Figure 1.