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Multi-Wavelength Properties of Be/X-Ray Binaries in the Magellanic Clouds

A.F. Rajoelimanana[1*], **P.J. Meintjes**[1], **P. A. Charles**[2,3]

[1]*Department of Physics, University of the Free State, PO Box 339, Bloemfontein 9300, SA*
[2]*School of Physics and Astronomy, Southampton University, Southampton SO17 1BJ*
[3]*Astrophysics, Cosmology and Gravity Centre, Department of Astronomy, University of Cape Town, Rondebosch 7701, South Africa*

E-mail: rajoelimananaa@ufs.ac.za

We present our study of long-term properties of Be/X-ray binaries (BeX) in the Magellanic clouds using archival optical photometry from the massive astrophysical compact halo object (MACHO) and optical gravitational lensing experiment (OGLE) IV projects. We combined these with optical spectroscopic observations obtained with the Southern African Large Telescope (SALT) to provide an understanding of their multi-wavelength properties. As an example we report some of our results on our study of the most extreme BeX source A0538-66 and discuss the implications of its system parameters on the observed multi-wavelength variabilities.

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*Speaker.

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1. Introduction

High mass X-ray binaries (HMXBs) are binaries that consist of a neutron star or a stellar mass black hole accreting matter from a massive ($\gtrsim$ 10 $M_{\odot}$) early-type (O or B) companion star. The vast majority of HMXBs are BeX systems consisting of a neutron star (usually an X-ray pulsar) orbiting a rapidly rotating Be star in a wide ($P_{\rm orb} \sim 10 - 300$ d) and (often highly) eccentric orbit ($e \geqslant 0.3$) [1]. Because of this high value of orbital eccentricity, BeX systems are transient sources with X-ray and optical outbursts (lasting for a few days) occurring only near the time of periastron passage where the neutron star is closest to the circumstellar disc around the Be star. These are known as type I (or normal) outbursts ($L_X \sim 10^{36-37}$ erg s^{-1}) and are modulated on the orbital period. Occasionally, BeX systems also exhibit giant (type II) outbursts which are much longer (lasting for several weeks) and brighter ($L_X \geqslant 10^{37}$ erg s^{-1}) than normal outbursts, and can occur at any phase of the orbit [2, 3]. A detailed review of the observational properties of BeX systems may be found in [1].

The Magellanic Clouds, particularly the Small Magellanic Cloud (SMC), are well-known for hosting an unusually large number of HMXBs when compared to our Galaxy. This overabundance is believed to be associated with its recent ($\sim$ 40 Myr ago) burst of star formation and its lower metallicity compared to the Milky Way. The most recent catalogue of SMC HMXBs compiled by [4] lists 121 confirmed HMXBs. Among these, 63 sources show X-ray pulsations with periods ranging from 0.717 s to 4693 s, indicating the presence of a neutron star. The optical counterparts of all these Magellanic cloud HMXBs are now confirmed as rapidly rotating non-supergiant O-B type stars with only one exception, the supergiant system SMC X-1 [5, 6]. This large sample of massive X-ray binaries in the SMC is extremely valuable because of its well known distance and low interstellar extinction.

In BeX systems, the compact object accretes matter directly from the circumstellar disc around the Be star. This means the strength of X-ray emission due to accretion depends strongly on the size and density of the disc which is the main reservoir of material available for accretion. The observed optical radiation comes primarily from the early-type O-B star and its circumstellar disc. In this proceeding, we report the results of our study of the long-term properties of BeX systems in the Magellanic clouds using optical light curve from the MACHO and OGLE project and spectroscopic observations obtained with SALT/RSS.

2. Long-term variability

BeX systems have been known for a very long time to show long-term periodic changes in their emission line profiles [7]. However, due to the lack of very long-term optical monitoring, the photometric variability of these systems has never been studied in detail. Such constraints have been alleviated over the last couple of decades, thanks to the long-term photometric monitoring projects, MACHO and OGLE. The MACHO [8] and OGLE [9, 10] projects have regularly observed the Magellanic clouds since 1992, and provide $\sim$ 24 yrs photometric observations of millions of variable stars, including most of BeX systems in the Magellanic clouds. The MACHO and OGLE light curves have been proven to be effective in the search of evidence for orbital modulation which are visible as a series of precisely regular outbursts [11, 12, 13, 14, 15, 16, 17, 18]. Apart from this

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modulation, BeX systems also show variations which are much longer than the orbital period and are referred to as superorbital modulations. The Large Magellanic cloud (LMC) source A0538-66 is the prototype for such behaviour [19, 20]. In A0538-66, these superorbital variations are quasi-periodic with a period of 421d. [20] suggested that these were related to the variation in size of the circumstellar disc around the Be star.

Analysis of the MACHO and OGLE light curves of all BeX systems revealed that the majority of them show periodic or quasi-periodic superorbital modulations on time scales of 200 – 3000d [16], which is suggested to be related to the formation and dissipation of the circumstellar disc around the Be star. Furthermore, the strength of the orbital outbursts varies significantly through the superorbital cycle. They are very strong either at optical maxima or at optical minima, depending on the inclination of the Be equatorial disc. Most BeX sources become redder when they brighten which is the opposite to what is seen in A0538-66, but that was explained as an inclination effect, with the equatorial disc of A0538-66 being viewed at high inclination angle. Figure 1 shows examples of long-term light curves of Magellanic Clouds BeX systems (A0538-66, SXP6.85) as well as their color variations.

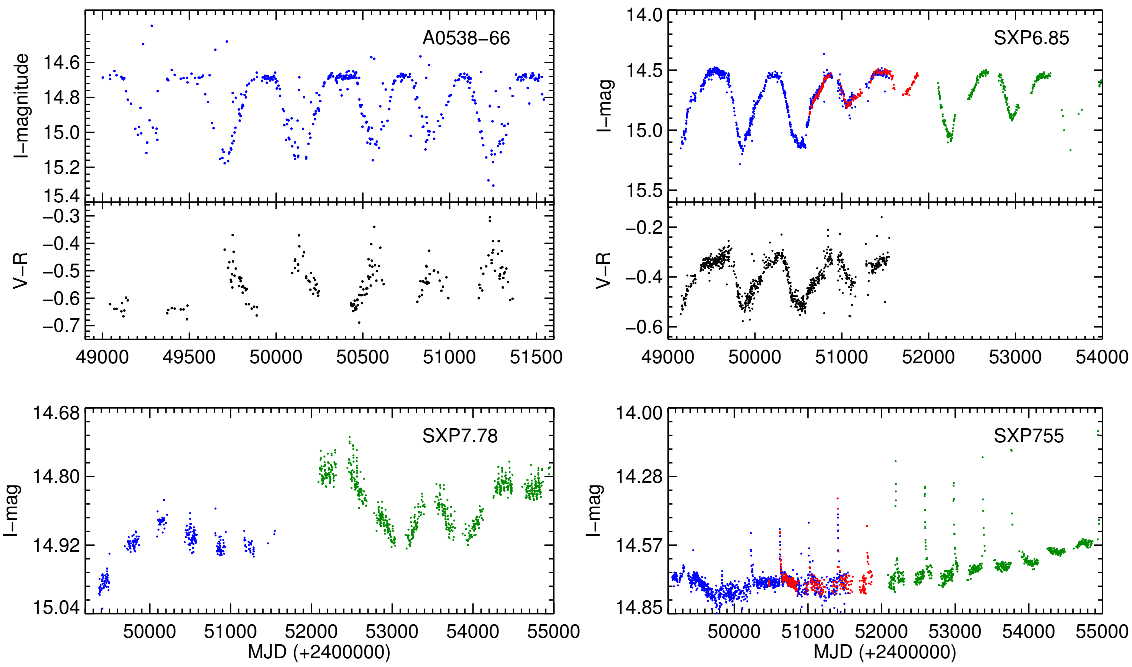

Figure 1: Top: Long-term light curves and MACHO color variations of the high inclination system A0538-66 (left) and the low inclination system SXP6.85 (right) showing quasi-periodic modulations. Bottom: light curves of the BeX systems SXP7.78 and SXP755 showing the variation of the outburst amplitude as a function of optical brightness. Adopted from [16].

3. Optical spectroscopy

Spectra of BeX systems are characterized by Balmer emission lines, most notably Hα, due to radiative recombination of ionized hydrogen in the circumstellar disc of the optical compan-

Table 1: List of Magellanic Clouds BeX systems in our sample.

Short ID	RA (J2000)	Dec (J2000)	V mag	$P_{\rm orb}$ (d)	$P_{\rm sup}$ (d)
SXP2.37	00:54:33.44	-73:41:01.3	16.3	18.58	–
SXP2.76	00:59:12.74	-71:38:44.9	14.0	82.37	2800
SXP6.85	01:02:53.31	-72:44:35.1	14.5	110.0	621
SXP7.92	00:57:58.51	-72:22:29.2	13.9	36.41	397
SXP8.80	00:51:53.16	-72:31:48.6	14.8	28.51	1798
SXP9.13	00:49:13.61	-73:11:37.8	16.5	80.10	1886
SXP15.3	00:52:13.99	-73:19:18.8	14.6	74.51	1515
SXP22.1	01:17:40.16	-73:30:50.6	14.1	75.97	–
SXP59.0	00:54:56.18	-72:26:47.8	15.2	62.10	–
SXP202A	00:59:21.03	-72:23:17.4	14.8	71.98	1220
SXP202B	00:59:28.67	-72:37:04.2	15.6	224.0	3000
SXP293	00:58:12.59	-72:30:48.8	14.9	59.77	–
SXP645	00:55:35.15	-72:29:06.6	14.6	135.3	2857
1A0538-66	05:35:41.00	-66:51:53.7	14.9	16.64	420

ion. This extended Be disc is also responsible for the strong infrared (IR) excess (due to free-free emission) seen in the spectra of Be stars. Therefore, any major change in the structure of the circumstellar disc can be inferred directly from Balmer emission lines whose strength and shape vary in time.

In order to follow the variation of the state of the circumstellar disc in BeX systems, we have observed a selected sample of Magellanic BeX systems from [16] (see Table 1) which display high amplitude quasi-period long-term variations in their light curves. The observations were done with the Southern African Large Telescope (SALT) [21] in a regular and systematic way throughout the super-orbital cycle. For each observing night, intermediate resolution and blue high resolution spectra were obtained using the Robert Stobie Spectrograph (RSS) [22, 23] in longslit mode.

The primary reduction of the data from each 2048×4096 CCD detector was done with the IRAF package PYSALT [24] which includes overscan, gain and cross-talk correction. Wavelength calibration, sky subtraction and flux calibration were performed using the standard IRAF software tasks in TWODSPEC. The spectra were flux calibrated using the sensitivity curve derived from the observed spectral energy distribution of spectrophotometric standard stars. Due to the design of the SALT telescope, an absolute flux calibration is not possible, however the overall spectral shape can still be recovered by applying a relative flux correction. Then, we extracted the one-dimensional spectra using the IRAF task APALL.

3.1 Full optical range spectra

We used two settings of the 900 lines mm^{-1} grating (PG0900) at two grating angles (12.5° and 20.0°) to cover the complete spectrum from ∼3100Å to ∼9000Å and provide a dispersion of 1.0 Å pixel^{-1}. The spectra were de-reddened using the LMC extinction derived by [25] of $E(B-V)$ = 0.12. Figure 2 shows an example of intermediate resolution spectra of BeX systems (A0538-

66) taken during the disc-less phase (2012 Oct 27), Be phase (2013 Jan 01) and at outburst (2012 Dec 28). Near the optical maximum (disc-less phase), the contribution from the circumstellar disc is negligible as the spectrum consists of pure absorption lines. This spectrum will give us direct information about the state of the underlying B star. However, during the Be phase (the disc is present) the Hα emission line, which is the result of radiative recombination from ionised gas in the disc, is very strong and double-peaked. During the optical outburst, the He II line at λ4686 appears which indicates the presence of hard ionizing X-ray radiation (with energy > 54 eV). This occurs only when the equatorial disc is sufficiently extended.

We have used the spectrum taken during the disc-less phase to estimate the stellar parameters. We compared it to a grid of synthetic template spectra convolved with Gaussian with Full Width at Half Maximum (FWHM) of 4.2 Å to match the resolution of our spectra. The spectra were also broadened to the corresponding rotational velocity derived from the high resolution spectra. We used the BSTAR2006 grid of a model spectrum from [26] which is a metal line-blanketed, non-LTE, plane-parallel, hydrostatic model atmospheres generated with the code TLUSTY [27]. An example of the result of the fit is shown in Figure 2 bottom panel.

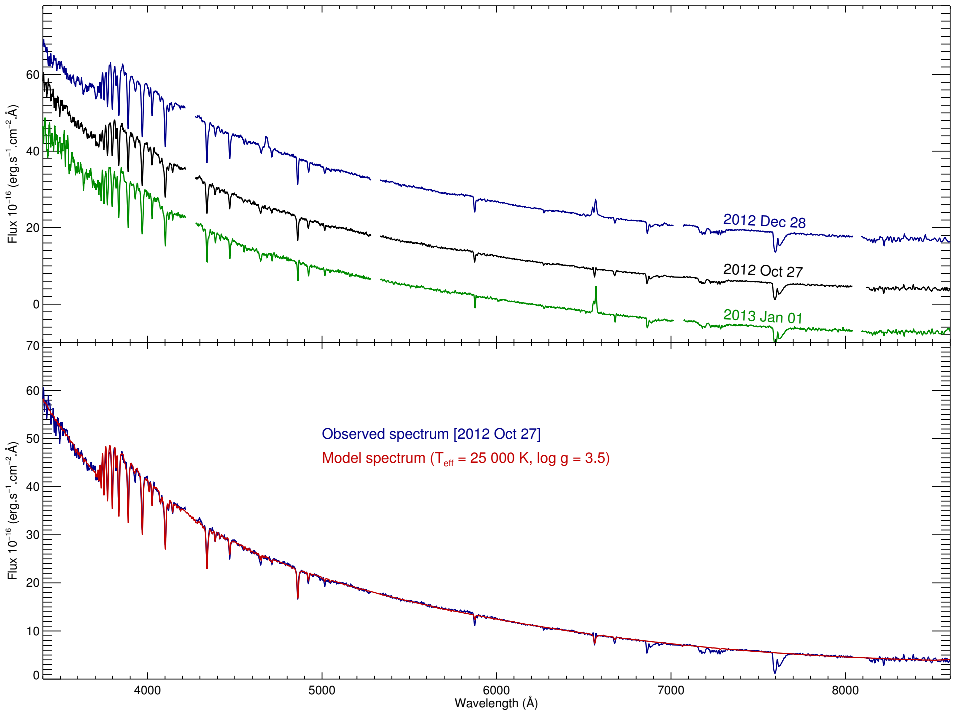

Figure 2: SALT/RSS spectra of A0538-66 taken during outburst (2012 Dec 28, blue), near optical maximum (2012 Aug 27, black) and during the Be phase (2013 Jan 01, green). The spectra obtained during outburst and Be phase are shifted vertically to illustrate the spectral changes. Note the presence of the He II λ4686 in the spectrum obtained during outburst. *Bottom:* Spectrum of A0538-66 taken on the night of 2012 Aug 27 compared to the best fit model with $T_{\rm eff}$= 25000 K and log$g$ = 3.5. The observed spectra were de-reddened using an extinction of $E(B-V)$ = 0.12. The gaps in the spectra are CCD gaps. Adopted from [28].

3.2 High resolution spectra

The high resolution spectra were obtained with the 3000 lines mm^{-1} grating (PG3000) at an angle of 40.5° which gives a spectral resolution of 0.7 Å, a dispersion of 0.23 Å pixel^{-1} and covers a wavelength range of ∼4000 – 4700Å. This allows us to derive accurate spectral classifications, measure the rotational velocities and to construct a radial velocity curve. Because of the low metallicity of the SMC, the spectral classification of B-type stars based on the metal-helium ratios is difficult. Therefore, to classify our sources, we use the temperature criteria suggested by [29, 30] which is based on the presence of the He II (λ4200, λ4541, λ4686) lines for the earliest subtypes and on the metal line strengths for the latest subtypes. Around periastron, the strength of the He II absorption lines may be affected by weak He II emission originating from the transient accretion disc, therefore it is better to use spectra which are taken far from periastron for classification purpose.

Figure 3 shows high resolution SALT/RSS spectra of some BeX systems from our sample.

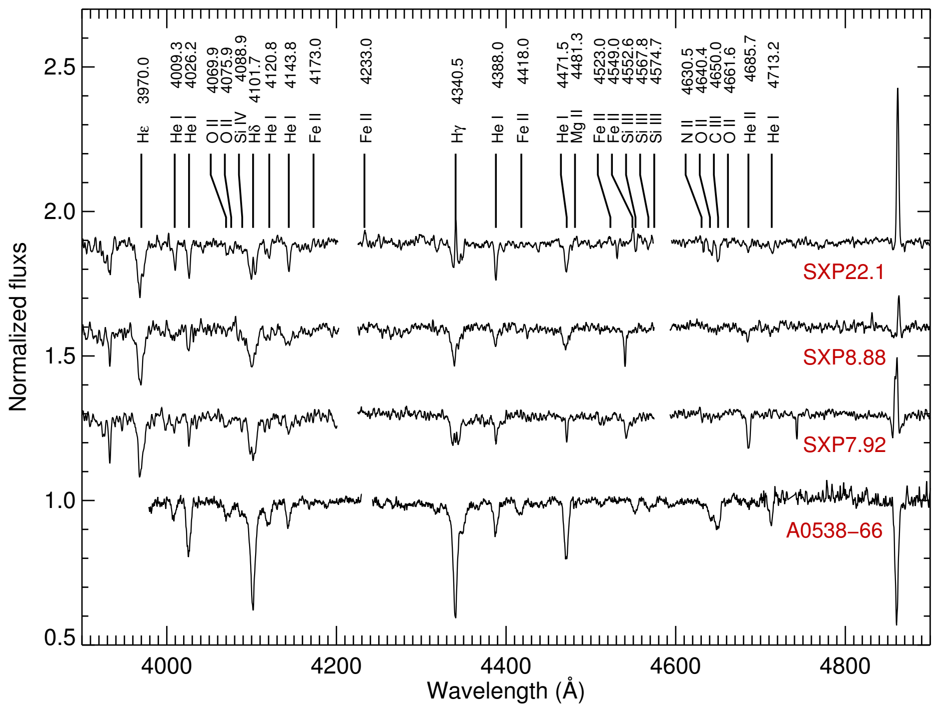

Figure 3: The observed SALT high resolution spectra of some BeX systems from our sample. The gaps in the spectra are CCD gaps.

We measured the rotational velocity using profiles of some He I absorption lines (λ4026, λ4143, λ4387 and λ4471) corrected for gravity darkening as proposed by [31]. The He I lines are less contaminated by emission from the Be disc compared to the Balmer lines, in addition these He I lines are quite strong throughout the B spectral sequence. We used the relation given in [32] to convert the FWHM of the lines to rotational velocities. For each source, we used the spectra taken during the disc-less phase (weakest Hα line) to minimize to the contamination from the circumstellar disc.

The radial velocities were measured by cross-correlating each individual spectrum against a rotationally and instrumentally broadened synthetic template spectrum of the same spectral type. We only use the region around the neutral helium lines at $\lambda 4026$, $\lambda 4143$, $\lambda 4387$ and $\lambda 4471$. The measured radial velocities were corrected to the solar system barycentre. The constructed radial velocity curve were then fitted with a Keplerian orbit by fixing the orbital period to the period obtained from the optical light curve. Figure 4 shows the radial velocity curve of the BeX source A0538-66, the orbital solution from the fit (left), as well as the geometry of the system (right).

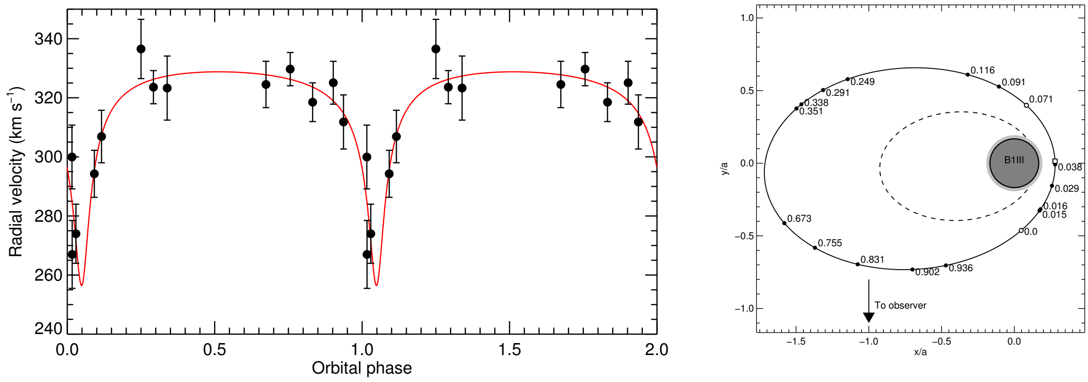

Figure 4: *Left:* Radial velocity curve of the Helium lines for A0538-66. The red line shows the orbital solution from the fit. *Right:* Geometry of the system, showing the relative orbit of the NS around the Be star computed using our orbital solution. Adopted from [28].

3.3 Hα emission

As the Hα emission line originates from the circumstellar disc, studying the evolution of its profile will give us information about the long-term structural changes which occur withing the Be disc. The Hα line in BeX systems exhibits a wide range of profiles such as single-peaked profiles, symmetric and asymmetric double-peaked profiles, shell profiles in which the central absorption that separates the two emissions extends below the stellar continuum and pure absorption. As an example, Figure 5 shows the evolution of the Hα profiles of the BeX system A0538-66. For A0538-66, the profiles varies both in time and as a function of the orbital phase. The single-peaked and double-peaked profiles are only seen in the spectra taken near periastron ($0.0 < \phi < 0.071$), where $\phi = 0$ is defined as the time when the maximum brightness is reached during outburst), and the symmetric shell profiles in the spectra taken outside periastron ($\phi > 0.071$). This means the nearly edge-on equatorial disc is unperturbed when far from periastron. Furthermore, all the double-peaked profiles are asymmetric with the red (R) component much stronger than the blue (B), consistent with our orbital solution in which the neutron star is moving away from us near periastron (see Figure 4 right panel).

4. Conclusions

The existence of these long-term monitoring project provides valuable informations on understanding the multi-wavelength properties of these massive binary systems. Because of the transient

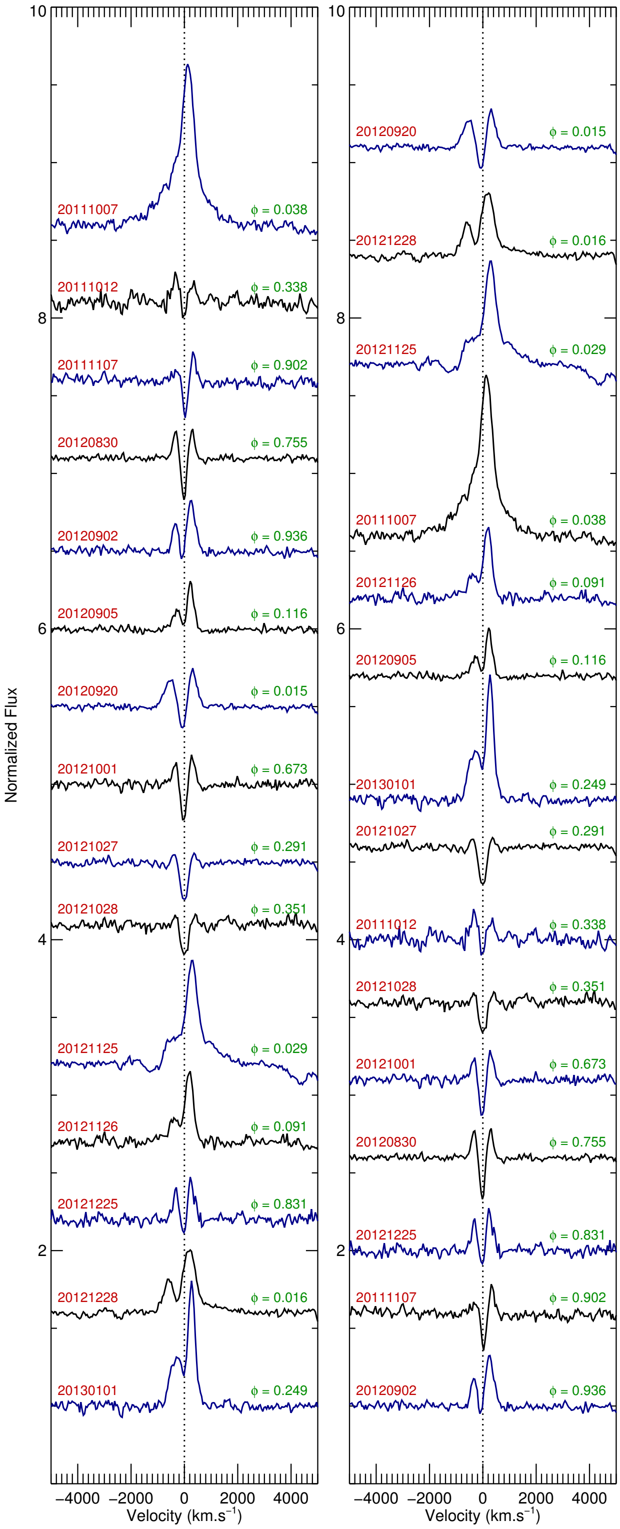

Figure 5: Evolution of the Hα line profile sorted in time sequence (*left*) and by orbital phase (*right*). The dotted lines indicates the rest velocity. Adopted from [28]

nature of the X-ray emissions in BeX systems, it is difficult to estimate the system parameters by using the radial velocities of the neutron star as we have no coverage of the X-ray pulsations over a significant part of the orbit. However, with optical spectra of a sufficient resolution and signal to noise ratio we are able to accurately classify and use the radial velocity of the optical companion to derive the system parameters.

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