A polarimetric census of Be X-Ray Binaries with FAPOL@NOT

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Abstract
Late O or early B stars showing Balmer lines in emission and infrared excess are classified as Be stars. Both, the emission in Balmer lines and the infrared excess, have their origin in a circumstelar disk-alike decretion structure. Rapid rotation and pulsations are known to be part of the mechanism of formation of such a structure but the process is still unknown. Be stars are also known to show a characteristic polarization due mainly to electron scattering of photons in the disk. Size of the disk, density and orientation with respect to the observer are factors that influence the total degree of polarization observed. They also present a characteristic variation of polarization with wavelength. Be stars accompanied by a compact object (neutron star or black hole) are the most common type of x-ray binary systems with massive optical companion. In these systems, known as Be X-Ray Binary systems (BeXRBs), the disk-alike structure is more compact and dense than that in isolated Be stars. We have started the very first polarization census of BeXRBs, with the goal to identify peculiar objects and compare the polarimetric porperties of Be stars in binary systems with the isolated ones. We present here the very first results of the survey, showing that Be stars in BeXRBs tend to show higher degrees of polarization than those of isolated Be stars and helping to identify and study some peculiar targets.

Keywords: x-ray binaries; polarization; stars:emission line; stars:Be

1 Introduction

Be stars are active early B or late O stars which develop an equatorial wind-fed structure in the form of a circumstellar disk (Rivinius et al., 2013). This disk-alike circumstelar structure is responsible of the following observational properties, which charaterize the Be stars as a class:

- IR excess with respect normal O/B starrs
- Balmer lines in emission or partially filled with emission
- Linear polarization expected with polarization degrees on the order of $\sim 2\%$ (Poeckert et al., 1979)

The latter of these observational properties of Be stars is not typically used as a part of the definition of the Be phenomenon, but we want to emphasize it because linear polarization arises naturally from the presence of such a cirsumstellar disk-alike structure, mainly due to electron scattering (Zellner and Serkowski, 1972; Poeckert et al., 1979). However, in some cases, due to the intrinsic difficulties in measuring polarization from stellar objects, it can not be measured nor estimated (Tinbergen, 2005).

When Be stars are accompanied by a compact object in a binary system, interaction of the compact object with the circumstellar disk of the Be star results in X-ray emission, leading to the definition of the most common type of x-ray binary with stellar massive companion, the so-called Be X-Ray Binary Systems (BeXRBS, see Reig, 2011).

The presence of the compact object, by means of tidal forces, will alter the structure and dynamics of the circumstellar disk. Some of the most common observed effects are (Reig, 2011):

– Disks in BeXRBS are smaller and denser than those in isolated Be stars, due to disk truncation

– Density perturbations can be enhanced of induced by the proximity of the compact object, leading to variability in Balmer lines profiles

The measured degree of linear polarization in Be disks depends on the size of the disk, its density, and the inclination angle with respect to the observer (Poeckert et al., 1979). With smaller and denser disks in BeXRBS than in isolated Be stars, and the disk dynamics affected by the tidal interactions, the degree of linear polarization provides a direct insight into the dynamics of the binary system.

There is, however, an important problem in obtaining the degree of linear polarization from stellar objects, and it is the induced linear polarization from the interstellar medium (see, Clarke, 2010). The linear polarization due to the presence of particles, dust or molecules in the interstellar medium is added as a vector to the intrinsic linear polarization of the observed stellar object (Jones and Whittet, 2015). Therefore the result can have a large range of effects, from over amplification to cancellation, depending on the result of the vector addition of both contributions. If the intrinsic polarization of the Be star in a BeXRBS can be determined, it ill provide relevant information related to its disk geometry (inclination with respect to the observer) and dynamics (changes in size, precession, density waves).

We started a systematic observational campaign of linear polarization from BeXRBS in Johnson-Cousins bands from the Nordic Optical Telescope, with the goal to characterize the polarization properties of BeXRBS as a group, test it as an indicator of disk state and evolution, compare it to expected levels of polarization from isolated Be stars, and identify peculiar or interesting targets.

2 Observational campaign.

An observational campaign on a large sample of BeXRBs was started on October 2018. Observations included linear polarimetry with FAPOL@NOT in the Johnson-Cousin bands U, B, V, R, and I, optical photometry in the same bands (to provide an estimation of interstellar extinction A_V, directly related to the expected contribution to the polarization from the interstellar medium), and, when possible, high resolution Hα spectroscopy (as it provides also information about the disk).

FAPOL@NOT[1] works in combination with ALFOSC[2] (Alhambra Faint Object Spectrograph and Camera) and allows an easy determination of the Stoke parameters Q and U thanks to the use a half-wave plate together with a calcite (which acts as a beam spliter in two orthogonally polarized beams). The half-wave plate is rotated 4 times in angles of 22.5, and a picture is recorded for each angle. A combination of the intensity of the two images of a star produced by the beam splitting on the four pictures is used to directly obtain the normalized Stoke parameters q, and u and the angle

[1]http://www.not.iac.es/instruments/alfosc/polarimetry/linpol.html

[2]http://www.not.iac.es/instruments/alfosc/

	Pol. Degree (%)					Pol. Angle (deg)					
Target	U	B	V	R	I	U	B	V	R	I	$p_{V int}$ (%)
LSI61303	0.99± 0.08	1.26± 0.05	1.10± 0.04	1.45± 0.05	1.25± 0.04	70± 2	65± 1	63± 1	65.5± 0.9	67± 1	3.4
MWC148	2.88± 0.10	3.78± 0.21	3.92± 0.07	3.96± 0.08	3.30± 0.08	85± 1	78± 2	77± 1	79.8± 0.5	80.4± 0.7	0.4
MWC656	0.67± 0.05	0.70± 0.04	0.66± 0.05	0.59± 0.06	0.62± 0.07	12± 2	10± 1	10± 2	18± 3	20± 3	–
PSRJ2032+4127	2.75± 0.12	2.10± 0.04	1.56± 0.05	1.15± 0.04	1.41± 0.04	45± 1	34± 1	33± 1	39.1± 0.9	36.6± 0.8	0.5
RXJ0440.9+4431	1.20± 0.06	1.22± 0.18	1.44± 0.07	1.45± 0.09	1.62± 0.08	77± 1	74± 4	69± 1	71± 2	75± 1	0.9
IGRJ06074+2205	4.93± 0.08	5.31± 0.03	5.61± 0.06	5.59± 0.07	4.98± 0.07	84± 0	77.1± 0.2	76.5± 0.3	80.7± 0.4	79.9± 0.4	0.2
SAXJ0635+053	1.47± 0.21	2.07± 0.13				91± 4	77± 2				0.4
1H2214+589	8.02± 1.19	8.31± 0.63	8.74± 0.64	6.52± 0.62	6.36± 0.46	40± 59	26± 2	27± 2	31± 3	3± 2	1.8
1A0535+262	0.95± 0.07	0.89± 0.05	1.00± 0.05	0.59± 0.06	0.96± 0.05	88± 2	79± 2	78± 1	84± 3	3± 2	0.1
1A0726-260	0.64± 0.35	0.39± 0.20	0.11± 0.28	0.15± 0.36	0.45± 0.35	35± 16	37± 14	13± 70	35± 67	3± 23	0.9
1H0556+286	1.32± 0.06	1.54± 0.02	1.65± 0.04	1.74± 0.06	1.48± 0.07	90± 1	82.7± 0.4	81+1	86± 1	83± 1	0.2
4U0115+63	4.04± 0.38	3.51± 0.11	4.38± 0.06	3.52± 0.04	3.19± 0.03	40± 3	48± 1	48.2± 0.4	53.0± 0.4	52.8± 0.3	3.2
4U2206+54	3.58± 0.07	3.90± 0.03	4.12± 0.07	4.16± 0.10	3.74± 0.11	22± 1	14.7± 0.2	14± 1	17.7± 0.7	18.4± 0.8	–
IGRJ01363+6610	5.58± 0.41	5.08± 0.71	4.68± 0.14	2.94± 0.15	3.56± 0.12	80± 2	61± 4	55± 1	59± 1	57± 1	3.3
IGRJ20006+3210	6.80± 0.42	5.28± 0.95	6.63± 0.21	6.37± 0.20	4.97± 0.13	11± 2	4± 5	7± 1	11.2± 0.9	15.0± 0.8	0.4
SAXJ01583+6713	8.23± 0.33	12.08± 0.71	11.75± 0.13	10.62± 0.13	9.38± 0.10	54± 1	49± 2	48.1± 0.3	54.1± 0.3	53.4± 0.3	1.1
EXO2030+375			16.7± 0.3	18.9± 0.2	17.89± 0.09			60 ± 1	64.0± 0.3	63.7± 0.2	1.4

Table 1: Summary of the measurements of polarization degrees and polarization angle for the observed BeXRBS.

of polarization of the incident beam. The intensity of each image of the star is measured with the technique of aperture photoemtry. The procedure is repeated for each Johnson-Cousins filter.

ALFOSC is a multipurpose and versatile instrument mounted on the Casegrain focus of the NOT, equiped with an e2V CCD which offfers a 6.4x6.4 arcminutes field of view in imaging mode. Due to vigneting, when the calcite is in the optical path, the field of view is reduced to 140 arcsec in diameter[3].

The initial campaign of 5 nights during October 2018 was complemented with individual target observations during the last 4 years. The list of observed targets, together with a summary of their observed degree of polarization and polarization angle is shown in Table 1.

3 Results

Table 1 shows a summary of the polarimetric measurements. The very first fact that arises from this table is that, in general, the polarization degrees obtained are larger than those expected for isolated Be stars (Poeckert et al., 1979).

Last column shows also the expected degree of polarization induced by the interstellar medium for those targets for which the interstellar reddening A_V could be estimated. As A_V gives a measurement of the quantity of interstellar material in the line of sight of the observed object, it is related to the expected amount of polarization induced by the interstellar medium (Clarke, 2010). A_V was estimated with the help of the photometric measurements. By comparing the polarization degree for the V filter with the expected contribution from the interstellar medium, we can have a first guess on which targets show clear hints intrinsic polarization. Those objects with polarization degrees equal or lower than the predicted from A_V will remain still uncertain. The interstellar medium induced polarization will add as a vector to the intrinsic one, therefore the result can be a lower degree or even no polarization at all.

A similar test has been performed by using the catalogue VizieR II/226[4] (An Agglomeration of Stellar Polarization Catalogues, Heiles, 2000) which gathers polarization measurements in the V band from

[3]http://www.not.iac.es/instruments/alfosc/polarimetry/

[4]https://cdsarc.cds.unistra.fr/viz-bin/cat/II/226

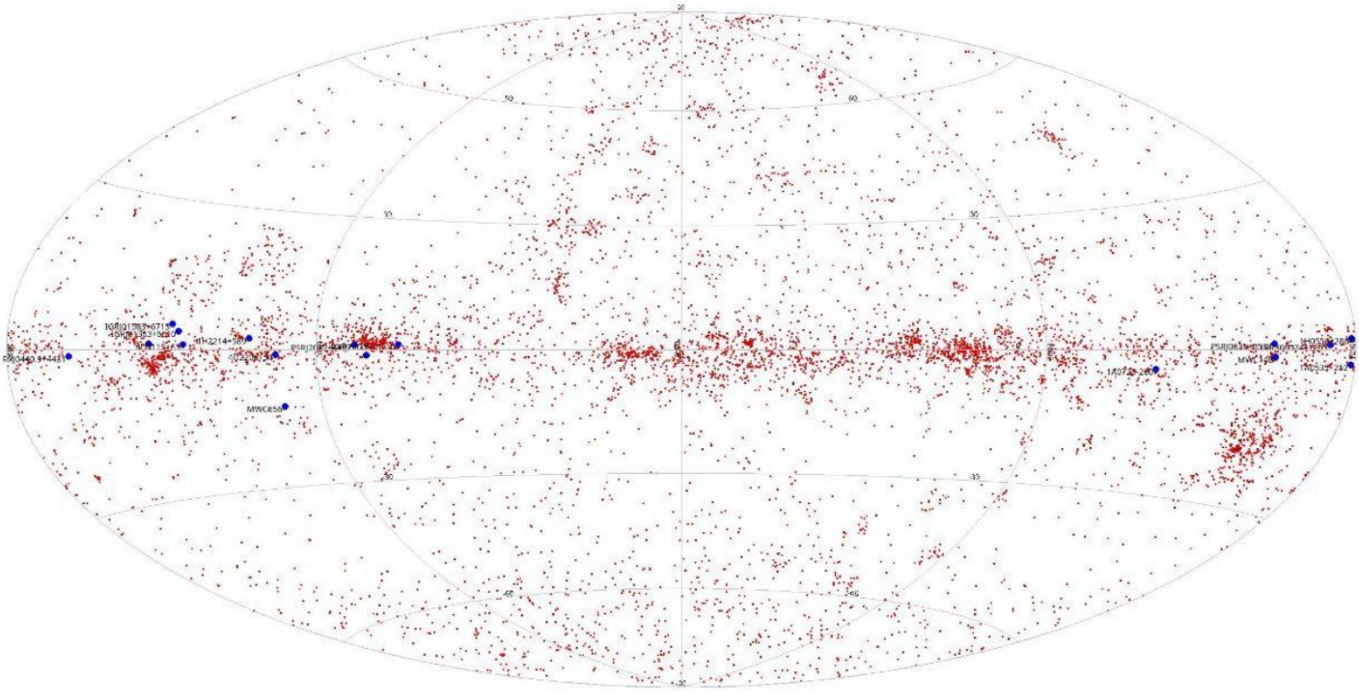

Figure 1: Distribution in galactic coordinates of the stars included in the VizieR II/226 cataloghe (red) and our targets (blue).

different catalogues. Figure 1 shows the distribution of objects of the catalogue (red) compared to the distribution of the observed BeXRBs (blue) in galactic coordinates. It can be seen that our targets are within areas that can be characterized, in terms of prevalent polarization degree and angle, by the catalogue stars. Stars in 1 are represented by ellipses, with the semi-major axis equal to the polarization degree of the star and the inclination of the ellipse equal to its polarization angle. In some cases (see Figure 2) there is evidence of a general tendency of stars in a sky area and a different behaviour shown by one of our targets. That can be indicative of intrinsic polarization but not conclusive.

Figure 3 shows the objects of the catalogue (red) and our targets (blue) in a polarization-parallax plot. Parallaxes where obtained from GAIA DR2 data ((Forveille et al., 2018). Some of our targets lie in the bulk of catalogue stars data, but a few of them clearly stand well above the general tendency of the catalogue data. We consider that a strong evidence of intrinsic polarization from those targets, as the sample of catalogue stars covers a very wide range of distances and are spread all over the galactic plane, being an statistically representative sample.

The polarization angles obtained represent directions perpendicular to the disk, but projected in to the plane of the sky. On the other hand, the shape of a double peaked Hα line can provide an estimation of the inclination of the disk with respect to the observer (Hummel and Hanuschik, 1997). We have compared the inclinations inferred from the Hα line with the polarization degree in the R band (which contains the HHα line) and the polarization angle in the same band. However errors in the determination of inclinations from Hα line measurements are very large. That makes impossible any attempt to find similitude or correlations.

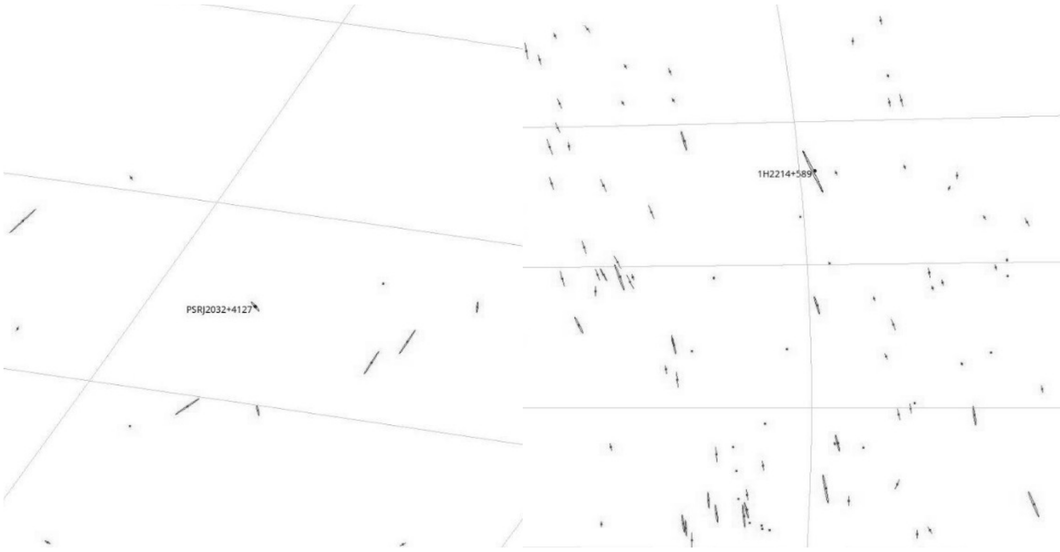

Figure 2: Zoom from Fig 1 into the region around two of the observed targets, namely PSR J2032+4127 (left) and 1H2214+589 (right).

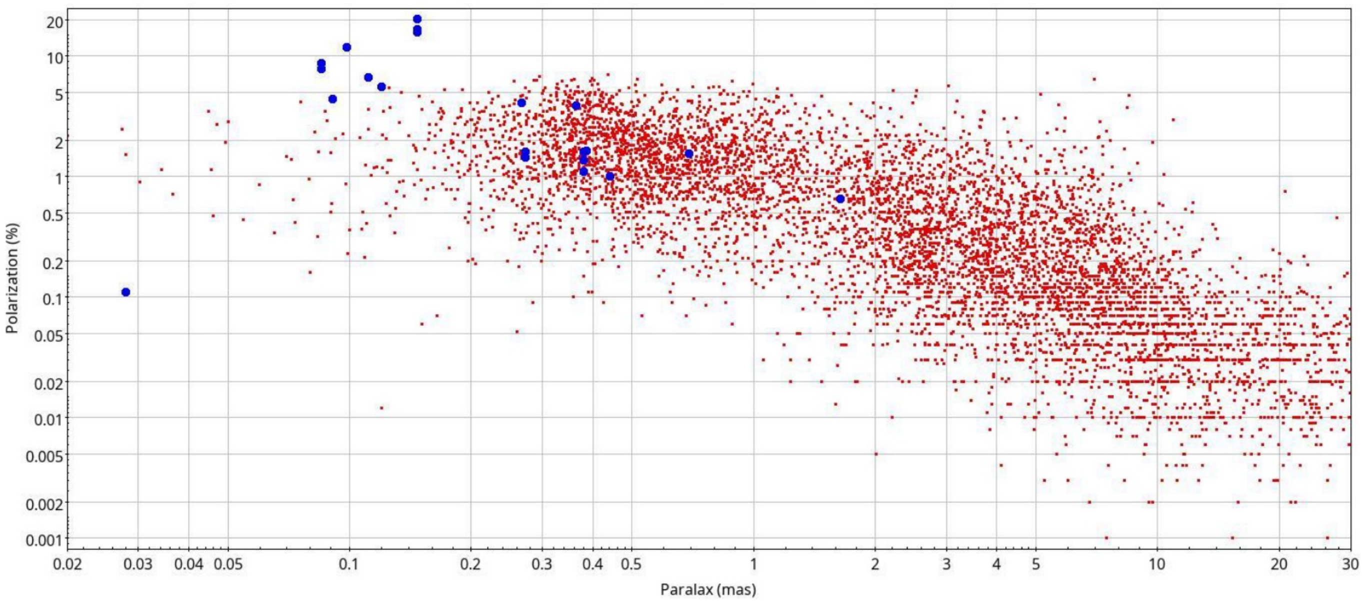

Figure 3: Polarization degree in the V band versus parallax for stars in the VizieR II/226 cataloghe (red) and our targets (blue).

MJD	Polarization (%)	Polarization angle (deg)	Interstellar polarization (%)	Interstellar pol. angle (deg)	Intrinsic polarization (%)	Intrinsic pol. angle (deg)
58403.1873	0.59±0.06	-11.0±3.0	1.3±0.4	-4±9	0.57±0.06	-23±3
59571.1183	0.80±0.06	-9.0±2.0	1.3±0.4	-4±9	0.74±0.06	-16±2
59577.0256	0.68±0.06	-5.8±2.6	1.3±0.4	-4±9	0.59±0.06	-15±3
59583.1255	0.67±0.06	-2.7±2.5	1.3±0.4	-4±9	0.57±0.06	-13±3
59624.9328	0.95±0.06	-8.0±2.0	1.3±0.4	-4±9	0.89±0.06	-16±2

Table 2: Measured polarization degree and angle for 1A0525+026, estimated interstellar polarization degree and angle from nearby stars, and corrected polarization to reflect the intrinsic one from the target.

4 Conclusions

Linear polarization represents a tool of great relevance to study circumstellar disks, their structure, and their evolution. We have made the first attempt to characterize BeXRBs in terms of their polarimetric properties.

Intrinsic polarization is very difficult to determine, as the interstellar medium makes this task complicated. We have attempted to determine the presence or not of intrinsic polarization, even if we can not state the actual value of the polarization degree or angle. A different and useful approach is to look for stars close by in the field of view and in distance, with the help of GAIA data. In the case of 1A 0535+026, for example, that has proven to be very useful, allowing for the determination of the most likely interstellar contribution to the polarization measured and an estimation of the intrinsic values (see Table 2). We have checked if in the VizieR II/226 catalogue there are coincidences in distance, both in the plane of the sky and in parallax, but with no lack. Therefore, a sample of stars close to our targets must be included in future observing campaigns in order to aid in the determination of the presence of intrinsic polarization and, in optimal cases, estimate the intrinsic values of the polarization degree and angle. Hα measurements are also a useful tool and ideal complement to our measurements, therefore, medium to high resolution Hα spectroscopy, allowing for a determination of disk parameters with small errors, will also be included in future observing campaigns.

As a summary:

- Polarimetry has been proven to be an ideal tool to study BeXRBs
- We have seen that in general, polarization degrees in BeXRBs are larger than those expected for isolated B stars
- We have identified some peculiar objects which deserve further attention

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