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Hot spot drift in synchronous and asynchronous polars: synthesis of light curves

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Abstract. In this paper, the effect of hot spots movement by accretor surface on the appearance of bolometric light curves for two types of polars - synchronous V808 Aur and asynchronous CD Ind is studied. The analysis was carried out under the assumption of a dipole configuration of the magnetic field, in which the axis of the dipole passes through the accretor center. It is shown that a noticeable shift of the flow maximum at the light curve corresponding to the position of the spots in synchronous polars is determined by a change in the magnitude of mass transfer rate. At the same time, the maximum deviation of the spots from the magnetic poles was 30°. In asynchronous polars, assuming a constant of the mass transfer rate, the spots movement caused by a change in the orientation of the dipole axis relative to the donor has a significant effect on the appearance of light curve. The greatest displacement of the spots from the magnetic poles, which equals to 20°, was observed at the moments when the accretion jet switched from one pole to the other. It is concluded that the comparison of synthetic and observational light curves provides an opportunity to study the physical properties of polars.

Keywords. close binary star, polar, MHD, flow structure, donor, accretor, hot spot, temperature map

1. Introduction

In our previous work [Bisikalo (2021)] we already investigated the movement of hot spots in synchronous and asynchronous polars. The three-dimensional pictures of the flow structure constrained by the results of numerical calculations and maps of the temperature distribution over the accretor surface together provide quantitative estimates of the hot spots movement. Such estimates are almost impossible to obtain directly from the observations of real polars. Therefore, in this paper for the purposes of comparison with observational data, we construct light curves.

2. Statement of a problem

Numerical MHD modeling of the synchronous polar V808 Aur [Gabdeev (2016)] allowed us to obtain a general picture of the hot spots movement by the accretor surface for different states of the binary system, which correspond to various values of the mass transfer rate. The analysis has shown that variations in the mass transfer rate form different patterns of the matter flow from the donor to the accretor: its high value leads to an elongation of the ballistic part of the jet trajectory and its significant deviation from the direction to the accretor; at lower values of the rate, the ballistic part of the jet gradually decreases and the main influence on the movement of matter is exerted by the accretor magnetosphere.

The maps of temperature distribution over primary component surface have shown that two energy release zones are formed in the considered synchronous polar: the first one (main) is in the vicinity of north magnetic pole and the secondary one is near the south pole. Hot spots are characterized by different intensities: the northern zone, corresponding to the accretion of matter from the jet, has a temperature about 5 times higher than the southern one, and this ratio persists with a change in the mass transfer rate. The position of hot spots is determined by the nature of accretion. The southern spot formed by the matter from the polar common envelope does not change its position with variations in the mass transfer rate. At the same time, its area decreases proportionally with a diminution in the binary system state. The temperature, on the other hand, experiences a slight increase with this change in the polar state, since the accretion of matter from the common envelope occurs more concentrated. This is accompanied by the growth in spot luminosity.

The location of the northern hot spot, on the contrary, significantly depends on the accretion rate. At the very high polar state, the spot has a maximum longitude offset relative to the north magnetic pole by about 30°. Its latitude deviation in this case is 5–7°. At the high state, the longitude offset decreases to 15°, while the value of the latitude of spot practically does not change, but the area of the energy release zone decreases by a factor of 2. At the intermediate state of the polar, the northern spot, while maintaining its geometric dimensions, closely approaches the magnetic pole. At the same time, its distance from the pole in longitude and latitude is 5°. Finally, at the low state, the northern region of energy release practically coincides with the north magnetic pole, its area decreases by a factor of 4 times compared to the very high state.

For the asynchronous polar CD Ind [Schwope (1997)], MHD modeling, which was performed at a constant value of the mass transfer rate, revealed the presence of jet switching processes from one magnetic pole to the other. In these processes, there is a noticeable change in the flow structure: the formation of an arch of matter in the region of magnetosphere, as well as the local accumulation of matter in the jet. The formation of these elements causes a significant change in the parameters of hot spots, their luminosity and position relative to the magnetic poles.

The constructed temperature maps for the asynchronous polar showed a number of features of the spots drift caused by the switching of the jet between the magnetic poles at a fixed value of the mass transfer rate. At the beginning of switching, the hot spot is located close to the pole which the jet will be re-connected to, it has a maximum area and a significant elongation along the longitude of the accretor. The moment of formation of an arch of matter in the inner region of the magnetosphere is characterized by a significant displacement of both spots relative to the magnetic poles: when they approach each other, the maximum distance from the pole is 20°. Due to the orbital rotation of the polar, the temperatures and accretion rates of hot spots at this stage differ by almost 2 times. Upon completion of the switch, the formed hot spot at the currently active pole retains a removal value of about 15°, and its temperature and area decrease slightly. It is worth noting that both switching processes follow the same scenario.

3. Results of calculations

For the purposes of comparing the results of numerical modeling with observational data, we synthesized bolometric light curves that allow us to separate the radiation flux of the hot spots from the rest part of the polar, since the latter have 2-3 orders of magnitude lower luminosity. In this paper, the synthesis of the desired light curves was performed by the method described in detail in one of our previous works [Sobolev & Zhilkin (2019)].

From the previously calculated temperature maps, the values of the displacement of hot spots relative to the magnetic poles are known, as well as the position of the poles themselves, so it is not difficult to identify areas corresponding to energy release zones on the light curves.

In Fig. 1 the bolometric light curves for the synchronous polar V808 Aur are presented. The upper panel of the figure shows a plot for the value of the mass transfer rate of $10^{-7} M_{\odot}$/year, and the lower one — for $10^{-10} M_{\odot}$/year. As it follows from the obtained temperature maps, these curves correspond to the deviation of spot from the pole equal to 30° and close to 0°, respectively.

In the figures shown, the apparent magnitude is plotted along the y axis, and the time scale in fractions of the orbital period (synchronous polar) and in orbital periods (asynchronous polar) is plotted along the x axis.

From Fig. 1, upper panel, it can be seen that the displacement of the maximum flow corresponding to the northern hot spot is 0.06 of the orbital period, which in the accepted angle reference system is 22°. Note that since the hot spot is an extended object, the displacement angle indicated for it refers to its center, which does not necessarily have the highest temperature. For this reason, the displacement value estimated from the light curve may not coincide with the value obtained from the analysis of temperature maps. The position of southern hot spot on this curve cannot be clearly distinguished, however, it is known that it does not change for all calculated values of the mass transfer rate. Thus, it can be argued that on this curve the location of spot will be the same as in Fig. 1, lower panel. If the south magnetic pole is in the orbital phase of 0.53, and the southern spot is in the phase of 0.49 (350°), then the value of the displacement of the latter is 0.04 of the orbital period, or 15°. The northern hot spot for the case of the minimum mass transfer rate practically coincides with the north pole, as follows from the temperature map.

In Fig. 2 the light curves for the asynchronous polar CD Ind are presented: the upper panel shows the moment of flow switching from the south magnetic pole to the north one, the lower panel — reverse switching from the north to the south pole.

For clarity, the plot shows in detail a fragment of the curve that coincides directly with the moment of switching (the 8th orbital period). When analyzing the asynchronous polar curves, it should be taken into account that the process of switching the jet between the magnetic poles proceeds quickly enough — within the fraction of the orbital period. This means that although it is possible to show all the phases of the process in detail during modeling, only the initial and final stages of the process are available to the terrestrial observer due to its location. On the observational light curve, the position of the hot spots will be fixed exactly at the specified time points.

As it can be seen from Fig. 2, the light curves for both accretion switching processes are almost identical and differ only in the value of the radiation flux. The position of the hot spots in this figure relative to the magnetic poles is shown as it will be seen by an Earth observer. The figure shows that the deviation of the northern energy release zone is 25°, the southern zone is about 30°, which is comparable with model calculations. Since the position of the spots in this polar is determined only by the dynamics of the switching process, in both cases it coincides. To display the motion of the spots accross the switching process, it is necessary to synthesize a separate family of light curves for the eighth orbital period, each of them will be shifted by a certain phase angle in tenths of a period.

4. Conclusions

The paper presents a method for analyzing the drift of hot spots in synchronous and asynchronous polars based on the construction of synthetic light curves. This method

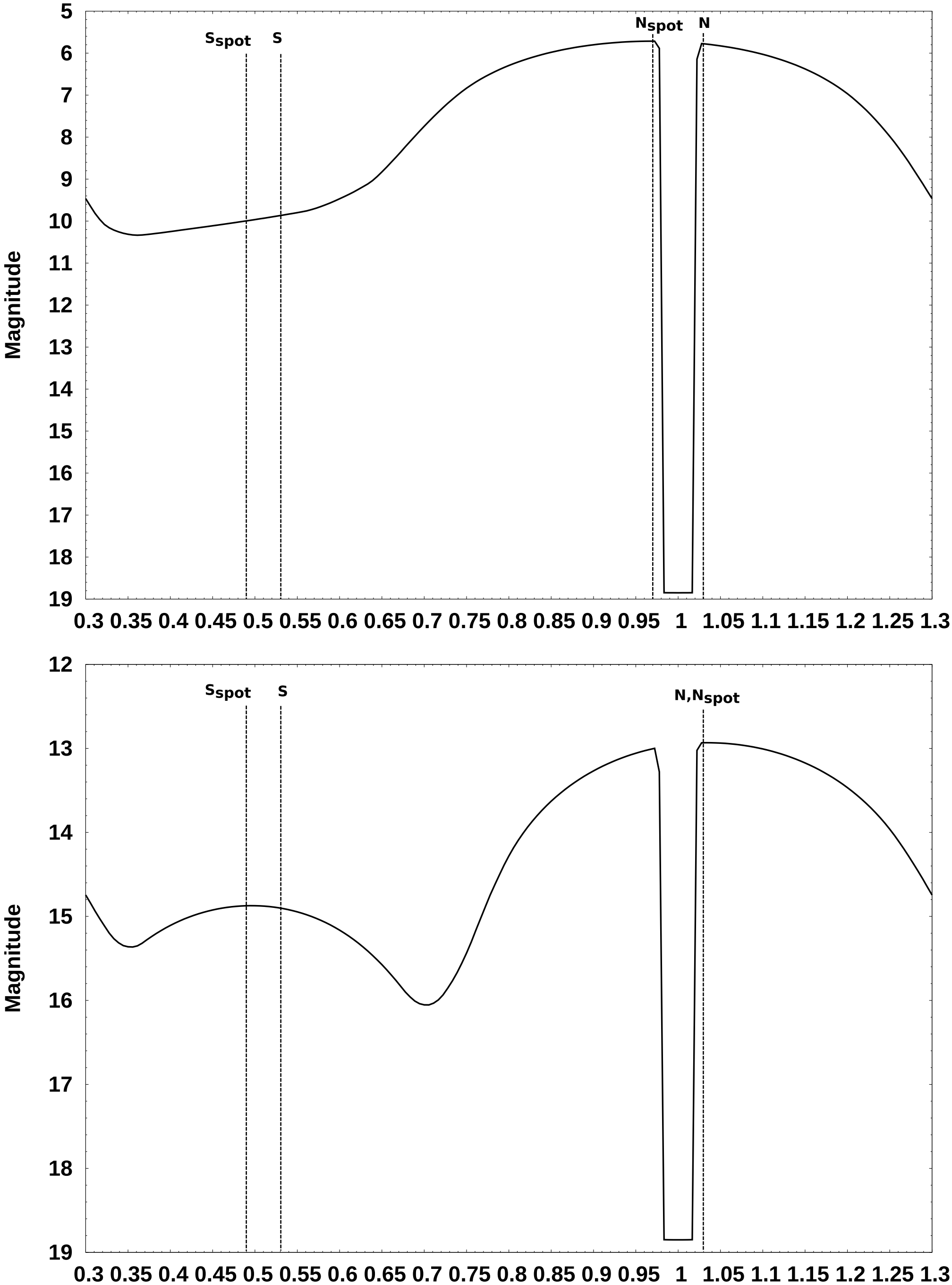

Figure 1. Synthetic bolometric light curves for the synchronous polar V808 Aur at a high state ($10^{-7}M_{\odot}$/year, upper panel) and at a low state ($10^{-10}M_{\odot}$/year, lower panel). The following values are indicated on the plot: N and S — north and south magnetic pole, $N_{\rm spot}$ and $S_{\rm spot}$ — northern and southern hot spot.

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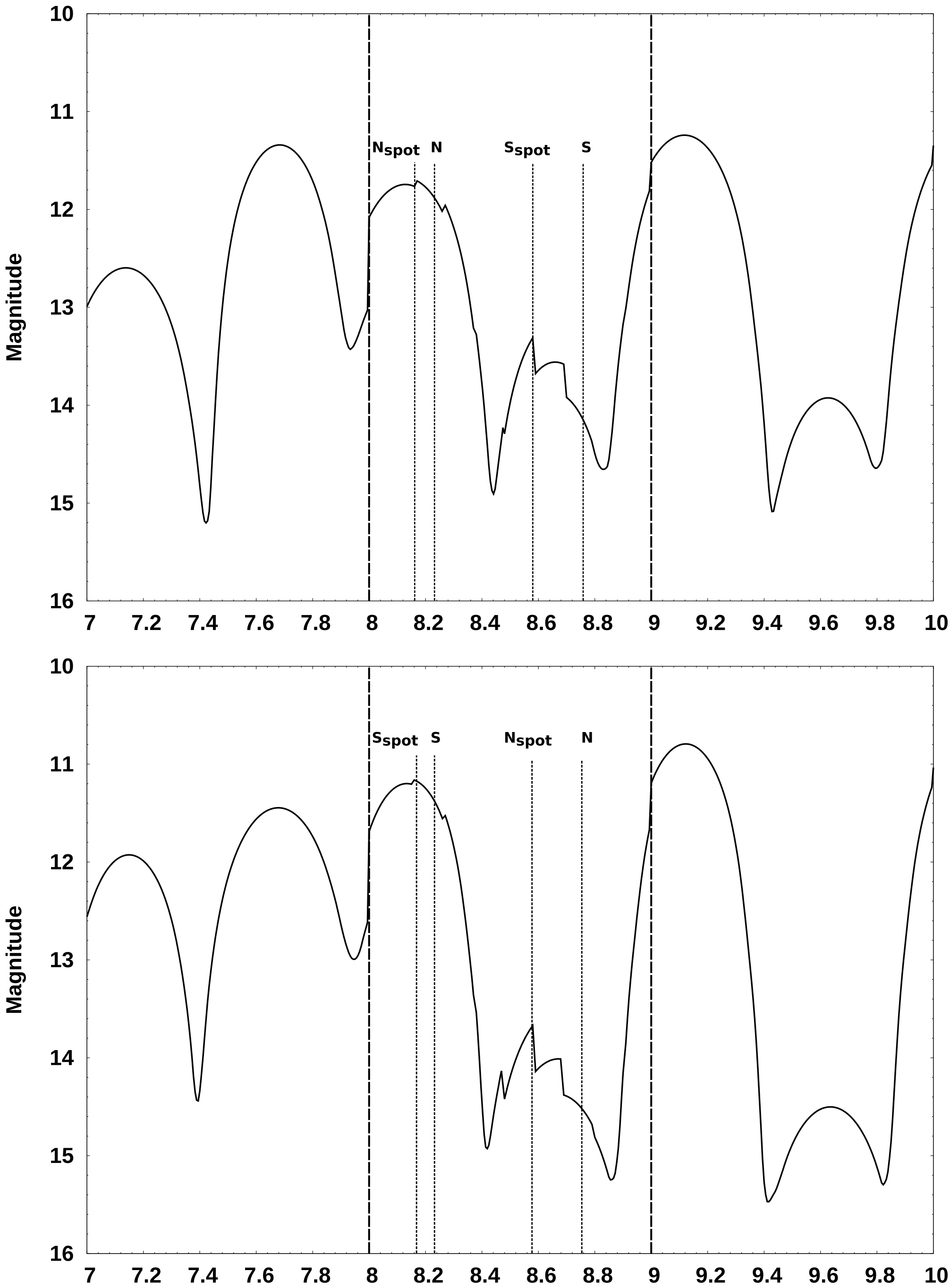

Figure 2. Synthetic bolometric light curves for the asynchronous polar CD Ind. It is shown a part of curve, corresponding to the moment of jet switching from the south pole to the north one (upper panel) and from the north pole to the south one (lower panel). Here the designations are the same as in the figure 1.

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has the following features. Its advantage is the possibility for direct comparison both the observational data and simulation results. This comparison provides a qualitative picture of the hot spots distribution and thus allows us to investigate the physical properties of polars. At the same time, the quantitative assessment performed by this method is ambiguous.

For example, according to the light curve, it is impossible to state certainly how the hot spot is displaced along the accretor surface. The movement of the spot along the star longitude leads to a shift of the maximum on a light curve, this moment can be fixed, but the shift in latitude cannot be unambiguously determined, since it leads to a change in brightness of the spot, and brightness variations may be caused by other reasons. In addition, as it was shown, the maximum on the light curve does not necessarily correspond to the spot center, so the deviation value of hot spots from the magnetic poles found on the light curves are approximate.

To display fleeting processes in polars, the duration of which is significantly less than the selected time scale, e. g., the orbital period, the presented method gives rough estimates. Therefore, a good tool for studying physical processes in polars will be the joint use of comparison of observational and synthetic light curves and numerical modeling.

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