The Dependence of the Characteristics of the Brightness Variability of Herbig Ae/Be Stars on the Orientation of Their Star–Disk Systems

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Abstract—We analyze the brightness variability of six Herbig Ae/Be stars: V1331 Cyg, LkHα198 = V633 Cas, AS 442, XY Per, V517 Cyg, and WW Vul. The last two objects are UX Ori stars showing Algol-like brightness dips with amplitudes of 2''0–2''5. AS 442 and XY Per also exhibit brightness dips but with considerably lower amplitudes, 0''3–0''6. On the contrary, such dips are not present in the light curves of V1331 Cyg and LkHα198, where stochastic variability with amplitudes of 0''1–0''2 on timescales of about a day can be seen. AS 442 and XY Per also show stochastic variability, but with lower amplitudes (≈0''05). These different types of variability could be related to the orientations of the star–disk systems. We suggest that the brightness variations in young stars whose disks are viewed edge-on are mainly due to non-uniform absorption, whereas the character of the variability in stars with pole-on disks is determined by non-stationary accretion. © 2001 MAIK “Nauka/Interperiodica”.

Herbig Ae/Be stars are currently thought to be young stars with spectral types earlier than F0 and masses from 2–10M☉ located in star formation regions. About 90 per cent of Herbig Ae/Be stars exhibit brightness variations, thought to be irregular with amplitudes varying from 0''1 (V) for the least to 3''–3''5 for the most active stars. As a rule, for stars with large variability amplitudes, a considerable fraction of the amplitude is contributed by so-called irregular Algol-like brightness dips. These are probably due to occultations of the star by circumstellar formations orbiting in a gas–dust disk [1]. Stars with Algol-like minima have been separated out as a special subgroup, named “UX Ori stars” after one of their most typical representatives.

Algol-like brightness dips make a considerable contribution to the light curves of only some of the most active UX Ori stars. In addition, most UX Ori stars alternate intervals of activity, with maximum variation amplitudes and many Algol-like dips in their light curves, and relatively quiet intervals with variation amplitudes of 0''3–0''6, which can last for years [2, 3]. During a quiet state, the shape of the light curve of a UX Ori star is fairly similar to those of ordinary Herbig Ae/Be stars.

The second important source of light variations in Herbig Ae/Be stars could be accretion of circumstellar matter onto the star. Accretion is an efficient source of energy; for example, the computations of Hillenbrand et al. [4] show that the accretion luminosity of some stars can be as high as 1200–1800L☉.

Grinin et al. [1] assumed that the photometric activity of UX Ori stars was closely related to their spatial orientation, and was highest when the angle i between the symmetry axis of the circumstellar disk and the line of sight was close to 90°. Grinin and Kozlova [5] attempted to relate the photometric activity to v sin i, i.e., to the orientation of the star–disk system.

We decided to analyze the light curves of several Herbig Ae/Be stars, based on the initial assumption that the circumstellar disks (envelopes) of UX Ori stars are viewed edge-on. We use many years of UBVR photometry acquired in the course of the ROTOR program at the Mt. Maidanak Observatory to analyze the light curves of the Ae/Be stars, and attempt to identify the origins of brightness variations.

From among the many stars observed, we selected six (WW Vul, V517 Cyg, AS 442 = V1977 Cyg, XY Per, V1331 Cyg, and LkHα198 = V633 Cas), whose light curves, in our opinion, can be subdivided into several subgroups. Below, we present the characteristics of the photometric variability of these stars.

WW Vul (A3ea) is a well known UX Ori star showing brightness dips with amplitudes exceeding 2'' in the V band. Its brightness and color variability have been analyzed in a number of studies (cf., for example, [6, 7] and references therein), and we accordingly use WW Vul only for comparison purposes. Observations of another star, V517 Cyg (A0–5), revealed brightness dips with amplitude 2''5 and photometric features similar to those of WW Vul [8]; combined with the presence of...
Hα emission split by a central absorption [9], these facts testify that this star is also a UX Ori variable. Typical light-curve fragments for V517 Cyg (1988) and WW Vul (1993) are presented in Figs. 1e and 1f.

Figures 1c and 1d show the dependence of $B-V$ on $V$ for these stars. We can see that $B-V$ becomes redder approximately in accordance with the interstellar reddening law during brightness dips. However, in contrast to classical UX Ori stars, the color tracks do not show any significant turn toward the blue. This is probably due to the small range ($<1''$ in $V$) of the brightness changes during the Algol-like dips: for UX Ori stars, the tracks turn at dip levels $\Delta m > 1''$ in $V$. However, there is some reason to suspect that the data points for some of the dips for AS 442 (Fig. 2c) are displaced toward the blue, while the data points remain at the reddening line during other, deeper, brightness dips. This effect could be real: similar behavior of color indices during Algol-like dips was observed for another UX Ori star, HR 5999 [14].

**Fig. 1.** Light-curve fragments for WW Vul, V517 Cyg, AS 442, XY Per, V1331 Cyg, and LkHα 198, demonstrating different photometric behaviors, depending on the orientations of the star–disk systems.
V1331 Cyg (F0) and LkHα 198 (A5) do not seem to experience Algol-like brightness dips. No light decrease of this kind was recorded in the 12 years of our observations. The light curves of these stars nearly always show stochastic variability with amplitude $0^\circ 1–0^\circ 2$ (Figs. 1a, 1b). Smooth brightness changes with timescales of 70 to 150 days are visible in the long-term light curves; these could be part of variations with still longer periods that

![Fig. 2. $V – (B-V)$ diagrams for the six stars showing different spatial orientations.](image-url)
could not be traced completely due to the limited duration of the observing seasons.

It appears from Fig. 2 that the ranges of the \( B-V \) variations for \( \text{V1331 Cyg} \) and \( \text{LkH\(\alpha\) 198} \) are even smaller than for \( \text{AS 442} \) and \( \text{XY Per} \), since the amplitudes of their \( V \) changes are smaller, and the tracks show no blueing effect.

Thus, we can tentatively subdivide the program stars into three groups:

Group I (\( \text{V517 Cyg, WW Vul} \)): Classical UX Ori stars, with the amplitudes of their brightness variations reaching \( 2.5-3^m \) (and amplitudes of Algol-like minima \( 2^m \));

Group II (\( \text{AS 442, XY Per} \)): Low-amplitude UX Ori stars, with the amplitudes of their brightness variations reaching \( 1^m-1.2^m \) and amplitudes of Algol-like minima \( \approx 0.5-0.7^m \); the light curves of these stars can display stochastic variability with amplitudes \( \approx 0.05^m \);

Group III (\( \text{V1331 Cyg, LkH\(\alpha\) 198} \)): Stars without Algol-like brightness dips, but showing stochastic variability with amplitudes \( \approx 0.2^m \).

In this subdivision, the Algol-like brightness dips have their maximum amplitude for \( \text{V517 Cyg} \) and \( \text{WW Vul} \) (Group I), a lower amplitude for \( \text{AS 442} \) and \( \text{XY Per} \) (Group II), and completely disappear for \( \text{V1331 Cyg} \) and \( \text{LkH\(\alpha\) 198} \) (Group III). The stochastic variability amplitude correspondingly increases from Group I to Group III.

Taken as a whole, the light curves in Fig. 1 demonstrate gradual changes of the variability characteristics.

Fig. 3. Long-term light curves of \( \text{V1331 Cyg} \) and \( \text{V517 Cyg} \).
Physical parameters of the six Herbig Ae/Be stars

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral type</th>
<th>$A_V$</th>
<th>$P$, %</th>
<th>$\nu\sin i$</th>
<th>$\text{EW}(H\alpha)$, Å</th>
<th>$H\alpha$ profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1331 Cyg</td>
<td>B0.5–F0</td>
<td>2.4</td>
<td></td>
<td>25</td>
<td>-48.4</td>
<td>P Cyg</td>
</tr>
<tr>
<td>LKHα 198</td>
<td>B3e–A5</td>
<td>4.5</td>
<td>1.87R</td>
<td></td>
<td>-66.3</td>
<td>Single</td>
</tr>
<tr>
<td>AS 442</td>
<td>B6–7</td>
<td>2.6</td>
<td>3</td>
<td>95–130</td>
<td>-18...-23</td>
<td>Double</td>
</tr>
<tr>
<td>XY Per</td>
<td>A2II+B6</td>
<td>2.3</td>
<td></td>
<td>15</td>
<td>-6</td>
<td>Double, single</td>
</tr>
<tr>
<td>V517 Cyg</td>
<td>A0</td>
<td>2.0</td>
<td>0.88</td>
<td>150</td>
<td>-20...-42</td>
<td>Double</td>
</tr>
<tr>
<td>WW Vul</td>
<td>A3e</td>
<td>0.48</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

from one group of stars to another. In our opinion, these differences in brightness variability can be explained as follows.

The disks of V517 Cyg and WW Vul are probably viewed edge-on (the inclination of the rotation axis to the line of sight is $i = 90^\circ$), so that the motion of gas and dust clouds along their Keplerian orbits leads to occultations of the central object, and therefore Algol-like brightness dips with amplitudes $\approx 2\sigma$.

According to McMuldrough et al. [15] and Bastien and Menard [16], the rotation axes of V1331 Cyg and LKHα 198, members of Group III, probably have inclinations to the line of sight $i = 60^\circ$. This conclusion was reached in [15, 16] based on an analysis of the orientations of the bipolar molecular flows observed for these stars, whose axes probably coincide with the stellar rotation axes. If these stars are also surrounded by disks, occultations of the central star probably do not occur, and there are different observing conditions for the innermost parts of the accretion disk, where the accretion is actually taking place. It is possible that these zones are no longer screened from terrestrial observers by the outer parts of the optically thick disk.

In this case, the stochastic variability in the light curves of V1331 Cyg and LKHα 198 could be the result of non-stationary accretion.

In contrast, the outer parts of the circumstellar disks of UX Ori stars screen the accretion zone, so that the stochastic variability is small or even absent. At some epochs, UX Ori stars also exhibit low-amplitude irregular variability, but we think that it is probably due to variable extinction in the disk rather than non-stationary accretion, though it is impossible to distinguish between these two possibilities without additional spectroscopic studies. Figure 3 presents the long-term light curves of V1331 Cyg and V517 Cyg, which, in our opinion, demonstrate changes in the character of the variability, depending on the orientation of the star–disk system.

AS 442 and XY Per probably have intermediate orientations. On the one hand, they still exhibit Algol-like brightness dips; on the other hand, stochastic variability appears in their light curves (Figs. 1c, 1d). The fact that, in some cases, the scatter of the data points in the light curves decreases during minima (occultations) provides evidence for a connection between the stochastic variability and non-stationary accretion in the stars’ immediate surroundings. It is also possible that the disks of these stars are more evolved than those of other UX Ori stars, so that the low amplitude of their Algol-like dips is due to the absence of circumstellar formations with high optical depth in their disks.

The table presents parameters from the literature that can be used to describe the orientations of star–disk systems. Generally speaking, the absorption, $A_V$, and degree of polarization, $P(\%)$, depend on orientation. On average, these parameters should be largest for stars with disks viewed edge-on. However, it is possible that the relation between these parameters and the orientation is not unique, due to the complex structure and dynamics of circumstellar formations and differences in the interstellar absorption. The value of $\nu\sin i$ may be a good orientation diagnostic. This quantity is known for three of our objects, and is consistent with our suggestions for the orientations of the three groups. The equivalent width $\text{EW}(H\alpha)$ and profile of the $H\alpha$ emission line are consistent with gradually changing inclination $i$ of the rotation axis to the line of sight. The flux in $H\alpha$ emission should increase with decreasing $i$, since we see an increasing area of $H\alpha$ emission, and, in addition, the screening of this zone by the optically thick disk decreases. Stars whose disks are viewed at low inclinations $i$ should show single $H\alpha$ emission profiles, whereas the $H\alpha$ lines in the spectra of stars whose disks are viewed edge-on should have double profiles divided by a central absorption [9]. The dependence of the intensity of emission lines and the appearance of the UV spectrum on the inclination of star–disk systems was considered by Blondel and Tjin a Djie [17].

We can see in Fig. 2 that, from one group of stars to the next, we observe a gradual increase of the slope of the color index–brightness relation of the star relative to the interstellar reddening line. Since the presence of hot gas influences the color indices, steepening this slope in the color index–brightness diagram, the change of the slope in Fig. 2 could be due to an increasing contribution from a gaseous component.

Another view is that the accretion rates of Herbig Ae/Be stars are not sufficiently high for variations in the accretion rates to give rise to the observed amplitudes of the short-timescale (stochastic) variability (for
example, [18] gives $\dot{M} = 10^{-8} - 10^{-7} M_\odot/\text{yr}$). Grinin [1] has suggested that, in this case also, the main source of variability remains variable circumstellar extinction; strong brightness dips are due to large gas–dust formations, while the short-timescale variability is associated with small inhomogeneities in the absorbing medium. As the orientation of the star–disk system changes, the amount of gas along the line of sight will decrease, but its influence on the brightness will remain fairly strong. In this model, the small changes of the color-index slopes relative to the reddening line in Fig. 2 can be explained as the result of differences in the mean sizes of the absorbing dust grains near different stars [19].

Let us now attempt to estimate the accretion rate needed to bring about the observed brightness variability ($=0''1-0''2$ in $V$). We will consider V1331 Cyg, using the following parameters determined by Chavarría [20]: $Sp = F_0$, $R_\ast = 5 R_\odot$, $M_\ast = 3 M_\odot$, $L = 90 L_\odot$, $T \approx 7400 \text{K}$, $A_V = 2_\odot^m 4$, and $r = 700 \text{ pc}$. Let us suppose that, during brightness minima, we observe only radiation from the star, and that the excess radiation observed during brightness maxima is completely due to accretion. We adopted the mean values for two subsequent dates, JD 2448427 and JD 2448428, for the low state ($U = 13.70$, $B = 13.19$, $V = 12.10$, $R = 11.04$), and the values for JD 2448509 for the high state ($U = 13.40$, $B = 12.91$, $V = 11.86$, $R = 10.83$). After converting the $UBVR$ magnitudes at the minimum and maximum brightnesses into radiation fluxes, $E_V (\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1})$, and taking interstellar absorption into account, we obtained optical spectral energy distribution (SED) curves for the star’s minimum and maximum states. Both curves grow appreciably towards the UV. Subtracting the first from the second curve, we obtain the curve of the radiation flux change, which also rises toward short wavelengths. The optical flux corresponding to this last curve is $=25\%$ of the flux generated by the star itself (i.e., the flux at minimum brightness), but the slope of the residual SED curve is less steep in the UV than the SED curve for the star. This means that the total flux due to accretion is less than 10 percent of the star’s luminosity. Using the known luminosity of the star and the formula $\Delta L = \dot{M} \frac{GM_\ast}{2R_\ast}$, we can estimate the accretion rates in units of $M_\odot/\text{yr}$. This yields $\dot{M} = 10^{-7} M_\odot/\text{yr}$, a fairly realistic value.

Confirmation of one or the other of these possibilities requires a more detailed photometric and spectroscopic study of Herbig Ae/Be stars with known orientations relative to the line of sight; in particular, it is necessary to determine whether these stars show correlations between the parameters of spectral lines emitted by hot gas and the character of their short-timescale variability.

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REFERENCES


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