Surface Flows and the Struve-Sahade Effect

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Abstract.  
The Struve-Sahade effect is the tendency for double-line spectroscopic hot-star binaries to show anomalously deeper absorption in the blueshifted profile, particularly for the secondary. This effect breaks the expected profile reflection symmetry at mirror opposite phases, which is not easily done. It was suggested at the meeting in Les Isles-de-la-Madeleine that this effect might be explained by surface flows induced by irradiation from the companion, but no effort was made to constrain the observational characteristics of such a flow. Here we apply a binary synthesis code to the generation of observable line profiles to characterize the required flow speed and geometry, and argue that the generation of such flows is a plausible, though not proven, explanation for the source of the Struve-Sahade effect.

1. Introduction

Spectroscopic binaries provide invaluable information about stellar mass as a function of spectral type, and even give size information for eclipsing binaries. To extend this information to isolated stars, it is necessary to correct for the ways the binary environment may alter the observed profiles. For example, standard binary synthesis codes include the reflection effect, whereby the illumination from the companion alters the surface brightness and line formation. However, despite the potential for radiation forces in close hot-star binaries, such codes do not normally include dynamical effects, such as the presence of winds or the possibility for induced surface flows.

Here we investigate the possibility that surface flows might help resolve the longstanding mystery of the Struve-Sahade effect. A particularly extreme example of this effect is seen in Figure 1, where at phase 0.91 (a phase where the secondary is approaching us and has not yet passed in front of the primary) a strange deepening of the blueshifted profile (from the secondary) is apparent.
Figure 1. Observed He I 4471 Å line in HD 152248 as a function of orbital phase. The primary star is on the left in both left panels, and on the right in both right panels. Note that one expects a mirror reflection in the profiles at opposite phases, but when one compares phase 0.91 to phase 0.115, it almost appears as though the stars have changed places. This is an extreme example of the Struve-Sahade effect.

relative to the nearly mirror-opposite phase 0.115. It almost appears that the primary and secondary stars have traded places in their orbit, because the profile has not been reflected through the center.

If the breaking of the reflection symmetry of the profiles from mirror-opposite phases is to be achieved via spatial structures, they must not be azimuthally symmetric about the line of centers. One suggestion of this type, by Gies et al. (1997), is that winds deflected by coriolis forces collide and generate asymmetric heating. Alternatively, if the symmetry breaking is to be accomplished with velocity flows, they can be azimuthally symmetric about the line of centers, so coriolis effects are not necessary and may even limit the extent of the effect. The approach taken here is to neglect the coriolis effects and consider how azimuthally symmetric velocity perturbations due to the transverse radiative driving may explain the Struve-Sahade effect.

The reason that transverse forces, rather than forces along the normal, are to be expected is that the flux normal to the surface is not altered by the companion, due to the need for radiative equilibrium. No such limitation exists
along the transverse direction, however. It might be expected that such forces could be balanced by pressure gradients induced by warps in the surface shape, but no scalar gradient can balance lateral radiative driving because such driving would exhibit a vertical shear and hence a nonzero curl. Thus dynamical effects are unavoidable; they merely await quantification.

To see how surface flows might produce the desired qualitative profile behavior, note that an approaching star has rotational speeds at its surface that are toward its companion, while the reverse holds for a receding star. Thus surface flows driven away from an irradiating companion would tend to oppose the rotational broadening on an approaching star, yielding a narrower and deeper line, and augment the rotational broadening on a receding star, causing the profile to appear less deep. The total equivalent width of the line is, of course, preserved by any induced surface flow, and this provides an important falsification criterion for this interpretation of the Struve-Sahade effect.

2. Equivalent Width Information

The importance of equivalent widths in the understanding of this effect has not eluded careful observers, and Sana et al. (2001) have analyzed the equivalent widths of a variety of photospheric absorption lines in a close binary over a full range of orbital phases. They fit Gaussian absorptions to both components of the double-line profiles, to separate the equivalent width contributions of each star. Their purpose was to test the above-mentioned explanation by Gies et al. (1997), and since this hypothesis involves actual increases in the equivalent width of the blueshifted profile, Sana et al. concentrated on quantifying this increase, and for that purpose Gaussian profile fits are adequate. They did not consider summing the total equivalent width over each double-line profile, so they could not test the possibility that non-Gaussian profile deformations could transfer apparent equivalent width from the redshifted to the blueshifted profile without altering the total, as would favor surface flows over asymmetric line-formation effects.

Table 1 gives the results of this type of analysis applied to equivalent widths compiled by Sana et al. (2001). The main purpose is to compare the change in total equivalent width of both profiles to the degree to which the approaching star shows enhanced apparent equivalent widths, relative to the receding star. The statistics displayed in the table are termed $EW$ and $SS$, where $EW$ sums the total equivalent width of the double-line profile at all phases where the primary is approaching and subtracts the mirror-opposite receding phases, and then normalizes by dividing by the simple sum of the total equivalent widths. The $SS$ statistic, on the other hand, sums the equivalent widths of all the blueshifted profiles, whether from the primary or secondary, and subtracts all the redshifted profiles, normalized in the same way. The results are expressed in Table 1 as percentages of the total equivalent width.

Since $EW$ measures the extent of any real changes in the total equivalent width as a function of observer orientation, Table 1 exhibits a fairly marked tendency to conserve total equivalent width in most lines. On the other hand, since $SS$ measures the apparent changes that might also arise from apparent equivalent width transfer from the redshifted to the partially overlapping blueshifted
profile, it is clear that such a transfer may indeed be occurring at a small but measurable level. This could result from surface flows not included in the Gaussian fits used to compile the statistics. The ratio $SS/\text{EW}$ is a measure of the extent to which the Struve-Sahade effect defies explanation in terms of changes in the actual line strengths, without invoking coincidentally strong cancellation effects. By contrast, surface flows can naturally generate a large $SS/\text{EW}$ ratio, and the results shown in Table 1 favor this interpretation for 7 of the 10 lines observed. For the other 3 lines, the evidence is marginal, or even contrary in the case of the O III 5592 Å line, so it is certainly possible that alternative explanations may be needed for some lines, and more data are desired to clarify this possibility.

<table>
<thead>
<tr>
<th>Line</th>
<th>EW%</th>
<th>SS%</th>
<th>SS/\text{EW}</th>
</tr>
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<tbody>
<tr>
<td>He I 4026 Å</td>
<td>1.6</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>He I 4471 Å</td>
<td>0.2</td>
<td>2.2</td>
<td>12.5</td>
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<tr>
<td>He I 4713 Å</td>
<td>3.6</td>
<td>9.4</td>
<td>2.6</td>
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<tr>
<td>He I 4922 Å</td>
<td>1.8</td>
<td>7.9</td>
<td>4.3</td>
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<tr>
<td>He I 5016 Å</td>
<td>1.1</td>
<td>6.8</td>
<td>5.9</td>
</tr>
<tr>
<td>He II 4200 Å</td>
<td>9.5</td>
<td>7.1</td>
<td>0.7</td>
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<td>He II 4542 Å</td>
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<td>1.5</td>
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<td>He II 5411 Å</td>
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<td>0.5</td>
<td>2.7</td>
</tr>
<tr>
<td>H $\gamma$</td>
<td>0.3</td>
<td>2.4</td>
<td>7.9</td>
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<tr>
<td>O III 5592 Å</td>
<td>12.2</td>
<td>5.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 1. Statistics derived from equivalent-width data of Sana et al.

Due to our neglect of coriolis effects (Podsiadlowski, comments at this meeting) and drag terms, the initial kinematic estimates of the flow speeds (Gayley 2002) gave unrealistically large values (Sana et al. 2001). This is in part due to the difficulty in determining the appropriate drag force (and see Koenigsberger, these proceedings) because kinematic viscosity is likely to be small relative to turbulent and magnetic effects. This seems especially true for trans-sonic flows, as expected here. Thus instead of attempting to calculate the flows \textit{a priori}, we will close here with a kind of plausibility argument for the estimated flow speeds required to show the effect in a clearly observable way, leaving quantification of the flow structure to planned future calculations.

Figure 2 shows the degree to which the blueshifted profile is deepened by flows away from the line of centers that build gradually over the companion-facing stellar surface to a maximum speed of 40 km/s, in a binary model similar to AO Cas. The details are purely heuristic, but the overall magnitude gives the sense that flows peaking at speeds of up to 40 km/s would yield an easily observable Struve-Sahade effect. Indeed, more subtle examples of the effect may require less supersonic speeds. Future work will center on determining if hydrodynamic models of the flow patterns support this general picture. Preliminary results are promising.
Figure 2. The heuristic Struve-Sahade effect that results from taking a flow away from the line of centers that gradually builds to 40 km s$^{-1}$, in a system like AO Cas. The model profiles are from the two quadratures, with the solid curve denoting the phase when the secondary is approaching. Blends somewhat deepen the blueshifted lines, but the magnitude of the Struve-Sahade effect may be seen by contrasting the change in depths between the two lines.

References

Gies, D. R., Bagmolo, W. G., & Penny, L. R. 1997, 479, 408
Discussion

Wolf-Rainer Hamann: Ken, I was just puzzled by one detail that you showed this morning. In the profiles calculated by Townsend, you showed there was a slow flow but it is not perfectly symmetric.

Ken Gayley: Yes, I’m puzzled by that detail as well. It’s a very good point. It seems to me these ought to be exactly symmetric. But the Townsend code includes everything. It’s not just the opacity of the He\textsc{i}\,λ4471 line; it’s everything that’s in the atmosphere. It’s an actual model-atmosphere code. So there could be other lines or other complicated processes. But I don’t really understand why these are not symmetric. This is especially true for \(\beta\) Sco, which is particularly non symmetric. Basically this code was created last week, so I wouldn’t be surprised if there’s still a few bugs to work out.

Ed van den Heuvel: The reflection effect must be in there.

Ken Gayley: Oh, good point. The gravity darkening effect is in there but I’m not 100\% sure if he included the reflection effect, which is the light of one star warming the photosphere of the other star.

Wolf-Rainer Hamann: Both effects will break the symmetry.

Hugues Sana: Just a comment. There is the O\textsc{ii} line to the left of He\textsc{i}\,λ4471 line.

Ken Gayley: OK, there are some blends going on that could complicate things.

Julian Pittard: Lovely work, Ken. I’m just wondering: Would you expect such a surface flow to change the driving of the wind in any fashion?

Ken Gayley: Not really. Basically the vertical structure shouldn’t be affected too much by this. Because the force scale in the vertical direction is so much larger, it’s almost ambivalent to what’s going on in the transverse scale. So I doubt that there’s any impact.

Sergey Marchenko: My immediate concern would be that you run into the shock practically right after you start this flow, because the flow is highly supersonic in the direction opposing the rotation. And then the shock will be highly dissipative, considering the densities involved. You will not go far after this shock; you interrupt the flow by this shocked region. Is there any way round it?

Ken Gayley: Well, this is a very important question that relates to the issue of what happens when you try to put a transverse supersonic flow in a star. And I have to begin by saying that the numbers I’m getting are barely supersonic. So it’s not obvious to me that it’s really required to go quite to 50 km/s to fit the profile.
Sergey Marchenko: But this is opposing the rotation. That will be highly supersonic.

Ken Gayley: Well, it is the reference frame of the rotating star which is probably the important reference frame. So it wouldn’t really matter which direction the flow’s going. But still, if it’s a 50 km/s flow, that’s supersonic and that may cause shocks. A very interesting question is what the effective viscosity is, which Gloria Koenigsberger also talked about in her models. Short of hydro simulations, I can’t really say with certainty that it’s possible to get a 50 km/s flow on the surface of a star, but it might be. Furthermore, it’s not clear yet if it’s necessary to have a velocity of 50 km/s. We could get away with 30 km/sec and still fit the profiles. I haven’t really fit the profiles yet.

Philipp Podsiadlowski: Well, as we discussed yesterday, we have a lot of the calculations already. A former student of mine, Martin Beer, has actually calculated the 3D circulation pattern in the irradiated stars in X-ray binaries. So we actually have a full 3D circulation pattern although there are some assumptions in there. But the basic circulation pattern is actually quite different from what you assumed. Because of the Coriolis force, the circulation is always in the direction of the rotation. On the side where you have the radiative force, it reaches typical velocities of almost sonic, typically half sonic. Then it’s decelerated and when it comes back it’s highly subsonic. And one of the things we’re going to do is to find out how it affects the absorption lines and even things like radial velocity determinations.

Ken Gayley: Thanks. You were referring to work I meant to mention by Beer and yourself that is in press or is in preparation. So I will be curious to look at that. However, it’s not immediately clear how the Coriolis force will affect this, because normally the Coriolis effect is perpendicular to the flow. Since my flow is transverse, I would expect the Coriolis effect to just be balanced by gas pressure.

Philipp Podsiadlowski: It will contribute.

Ken Gayley: Interesting things are happening on Jupiter, where the Coriolis effect is causing little red spots and that sort of thing. I’ll have to think about that, for sure.