Stars and their variability observed from space
C. Neiner, W. W. Weiss, D. Baade, R. E. Griffin, C. C. Lovekin, A. F. J. Moffat (eds)

ACCRETION SIMULATIONS OF η CARINAE AND IMPLICATIONS FOR THE EVOLUTION OF MASSIVE BINARIES

A. Kashi[1]

Abstract. This contribution presented high-resolution numerical simulations of the colliding wind system η Carinae, showing accretion of the primary wind onto the secondary star close to periastron passage. We found that the stellar winds collide and develop instabilities, mainly the non-linear thin shell instability, and form filaments and clumps. We also found that a few days before periastron passage the dense filaments and clumps flow towards the secondary as a result of its gravitational attraction, and are then accreted onto the secondary. We ran our simulations for a conventional model of stellar masses, $M_1 = 120$ M$_\odot$ and $M_2 = 30$ M$_\odot$, and for the high-mass model, $M_1 = 170$ M$_\odot$ and $M_2 = 80$ M$_\odot$, that was proposed to fit better the history of giant eruptions in the 19$^{\rm th}$ Century, as well as radial-velocity variations of spectral lines during recent spectroscopic events. The results of the simulations show that the accretion process is more pronounced in the high-mass model, and that the amount of mass accreted, as well as the duration of the accretion, are also fitted much better. Our findings establish η Car as the most massive binary system in the Galaxy. As our simulations demonstrate, the presence of a binary companion can have a huge influence on the evolution of massive stars, especially at later stages where it may undergo giant episodes of mass loss.

Keywords: Stars: massive, mass-loss, winds, outflows, accretion, accretion disks, binaries: general

1 Introduction

Massive stars involve physical processes that are not often seen in low mass stars, such as rotation at almost critical speeds, strong winds and eruptive outbursts (e.g., Heger & Langer 2000; Heger et al. 2000; Kudritzki & Puls 2000; Puls et al. 2008; Meynet et al. 2009; Davidson & Humphreys 2012; Vink et al. 2015). Perhaps the most interesting phenomena observed in massive stars are related to ithe fact that most of them ($\approx 70\%$ according to Sana et al. 2012) share their lives with a companion star, which may influence their evolution considerably (e.g., De Marco & Izzard 2017; Eldridge 2017; van den Heuvel 2017).

The massive binary system η Carinae is composed of a primary which is a very massive star at a late stage of its evolution, and a secondary which is a hotter and less luminous evolved main-sequence (MS) star (e.g., Davidson & Humphreys 1997, 2012). (e.g., Davidson & Humphreys 1997; Davidson et al. 2017), and strong winds (Pittard & Corcoran 2002; Akashi et al. 2006), resulting in a unique phase of strong interaction every 5.54 years during periastron passage known as the "spectroscopic event". During the event many spectral lines and emission at practically all wavelengths show rapid variability (e.g., Nielsen et al. 2007; Damineli et al. 2008b,a; Davidson et al. 2015; Mehner et al. 2015, and many refs. therein). The X-ray intensity, which also serves as an indicator of the intensity of wind interaction, drops for a few weeks, changing from one spectroscopic event to the other (Corcoran et al. 2015).

Soker (2005a) developed a model to interpret the line variations during the spectroscopic event as a result of accreting clumps of gas onto the secondary near periastron passages, disabling its wind. The suggestion was later developed into a detailed model accounting for various observations (Akashi et al. 2006; Kashi & Soker 2009b). An estimate of the amount of accreted mass during the spectroscopic event was first obtained by Kashi & Soker (2009a), who performed a detailed calculation, integrating over time and volume of the density within the Bondi–Hoyle–Lyttleton accretion radius around the secondary. Kashi & Soker (2009a) found that accretion should take place close to periastron, and that the secondary should accrete $\sim$ few $\times$ 10^{-6} M$_\odot$ each cycle.

The last three spectroscopic events, 2003.5, 2009 and 2014.6, were different from each other, and reflected a trend in the intensities of various lines (Mehner et al. 2015). Observations of spectral lines during the 2014.6 event were interpreted as weaker accretion onto the secondary close to periastron passage compared to previous events, indicating a decrease in the mass loss rate from the primary star. This 'change of state' of the primary

[1] Ariel University, 4070000 Ariel, Israel ; Email: kashi@ariel.ac.il ; ORCID:0000-0002-7840-0181

was identified by Davidson et al. (2005) and also predicted from numerical simulations by Kashi et al. (2016). Further indications of the change of state was found by comparing UV emission lines at similar orbital phases separated by two orbital revolutions, at positions far from periastron passage (Davidson et al. 2018).

Older grid-based simulations (Parkin et al. 2009, 2011) and Smoothed Particle Hydrodynamics (SPH) simulations (Okazaki et al. 2008; Madura et al. 2013) of the colliding winds did not accretion onto the secondary. Teodoro et al. (2012) and Madura et al. (2013) argued against the need for accretion to explain the spectroscopic event. But in spite of those claims, Parkin et al. (2011) simulated stationary colliding winds at the time of periastron and showed that unstable wind and clumps were formed and reached to distance that was very near the secondary. Since their simulations were unable to reach high resolution they could not obtain a clear picture of accretion, but they postulated that high-resolution simulations with "switching off" the initiation of the wind will be able to reveal a wind "collapse". These simulations did not include the gravity of the secondary either, but it was later found to be important for accretion to take place.

Akashi et al. (2013) also simulated the wind interaction, and found that clumps of gas were formed a few days before periastron passage owing to instabilities in the colliding winds structure, in agreement with X-ray flares observed at that time (Moffat & Corcoran 2009). Some of the clumps moved towards the secondary, and reached one grid cell from the secondary wind injection zone, implying accretion. However, the resolution of these simulations was not fine enough to see the accretion itself.

The simulations presented below extend those of Akashi et al. (2013) in the sense that they include (1) higher resolution that could trace the flow better, allow the development of instabilities, and reveal final details, and (2) more detailed physical treatment. The following discusses the results of our simulation and their implications for massive-star research.

2 Simulations and Results

The simulations were described in detail by Kashi (2017) and Kashi (2019). The final evidence for accretion came from the simulations of Kashi (2017) that included many more physical effects (e.g., gravity of the two stars, radiative cooling, radiation transfer, artificial viscosity), and showed the destruction of the colliding winds structure into filaments and clumps that later were accreted onto the secondary. They demonstrated that dense clumps are crucial to the onset of the accretion process. The clumps were formed by the smooth colliding stellar winds that developed instabilities, (mainly the non-linear thin shell instability, NLTI: Vishniac 1994)) that later grew into clumps (no artificial clumps were seeded). This confirmed the preceding theoretical arguments by Soker (2005a,b) who suggested accretion of clumps. Furthermore, as the simulations in Kashi (2017) included a radiation transfer unit which treats the photon-gas interaction, so the momentum of the accreted gas is being changed appropriately along its trajectory. It thus quantitatively showed that radiative braking cannot prevent the accretion, thereby confirming theoretical arguments given by Kashi & Soker (2009a). Kashi (2019) extended the simulations to treat *the response of a wind blowing star to mass that arrives with strong momentum and is accreted onto its surface*. Figure 1 shows the results for one of our simulations.

We found that accretion is obtained for both the conventional mass model ($M_1 = 120\ \mathrm{M}_\odot$, $M_2 = 30\ \mathrm{M}_\odot$) and the high mass model ($M_1 = 170\ \mathrm{M}_\odot$, $M_2 = 80\ \mathrm{M}_\odot$). For the high mass model the stronger secondary gravity attracts the clumps and we get higher accreted mass of $M_{\mathrm{acc}} \simeq \mathrm{few}\times10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ and longer accretion periods, in the order of a month, which more closely match the observed ones. We also calculated the increase in optical depth in any line of sight and the reduction in the effective temperature (T_{eff}) as a result. Observations of lines during the spectroscopic event indicate ionizing radiation from the secondary equivalent to that of a star with $T_{\mathrm{eff}} \lesssim 25\,000$ K. For reasonable and even high mass loss rates, only the high mass model we tested matched the observed decline in T_{eff} (Figure 2, right panel).

We ran a number of simulations with varying parameters (Figure 2, left panels). An important parameter we studied is the mass loss rate of the primary (see Kashi 2017). We found that the mass loss rate of the primary affects the accretion rate of the secondary in a non-linear way, and found a strong dependency between the accreted mass and the mass loss rate of the primary. The simulations showed that if the mass loss rate of the primary is lowered by a factor of a few the accretion can stop. Thwrefore, they supported the claim of Mehner et al. (2015), who suggested that, if the mass loss rate of the primary continues to decrease, future spectroscopic events will be very weak or might not occur at all (though a recent paper argues differently; Mehner et al. 2019).

Another parameter we varied is the eccentricity, for which we also tested $e = 0.85$. This value was favored by Davidson et al. (2017) because it gives the smallest possible separation distance at the beginning of the spectroscopic event. It was therefore expected that $e = 0.85$ would produce earlier accretion compared to $e = 0.9$, even though the periastron distance is 50% larger for the smaller eccentricity. Figure 2 shows our results, confirming that for $e = 0.85$ the accretion duration is indeed longer, and more mass was accreted. Run

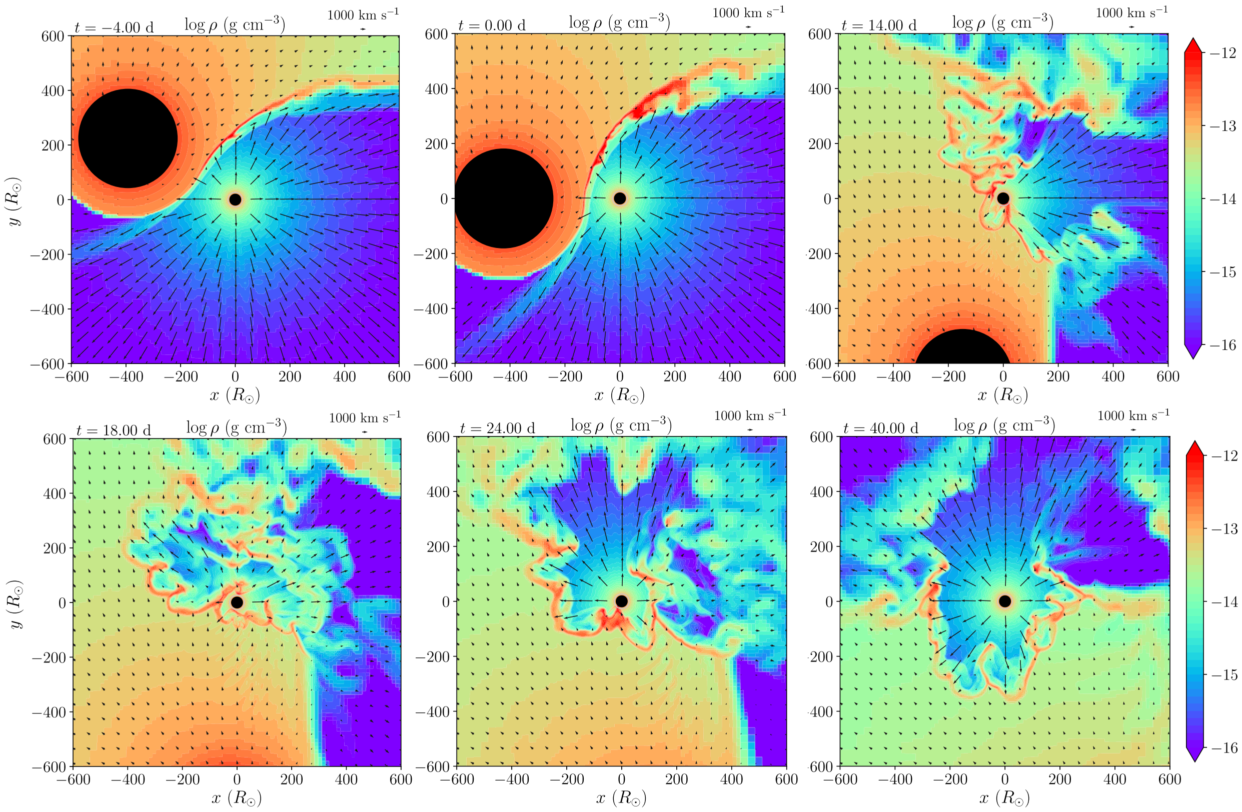

Fig. 1. Density maps with velocity vectors, sliced in the orbital plane ($z = 0$), for one of our runs with the high mass model for η Car, $M_1 = 170$ M$_\odot$ and $M_2 = 80$ M$_\odot$. The secondary is at the center (small black circle) while the primary (large black circle) orbits it counter-clockwise. Periastron passage occurs at $(x, y, z) \simeq (-1.9 \text{ au}, 0, 0)$ and $t = 0$. The colliding wind structure is destructed by instabilities and gas is accreted onto the secondary. The simulation shows how the secondary star wind is restored as the stars move away from each other after periastron passage.

M6 (high mass model, lower e) also showed early accretion exactly as expected by Davidson et al. (2017). For the conventional mass model (run C6) we did not see this behavior, because the larger periastron distance and smaller secondary mass combined to reduce the gravitational attraction of the secondary and therefore early accretion could not occur.

3 Conclusions

Our simulations prove that accretion takes place close to periastron passage. As expected from the studies of Soker (2005a) and Kashi & Soker (2009a), we found in Kashi (2019) that accretion causes the secondary star to stop, at least partially, blowing its wind. Quantifying the effect for a large parameter space requires an extensive effort of running many simulations and advanced post-processing of the results. So far we ran a number of cases that partially cover the parameter space (Figure 2). Our results support the high mass model for η Car, with a combined mass of 250 M$_\odot$, a result that was also supported by other considerations, such as the timings of periastron passages during the 1839–1858 Great Eruption (Kashi & Soker 2009a), and fitting radial velocity variations of spectral lines for present-day observations during the orbital motion, and especially close to periastron passage. (Kashi & Soker 2016).

As accretion takes place presently it certainly has occured during the Great Eruption of η Car, when the mass loss rate of the primary was at least a few thousand times larger than today. This makes the accretion model (Soker 2004; Kashi & Soker 2009a) the most probable scenario for the Great Eruption of η Car, and the formation of the Homunculus nebula. Very briefly, according to the accretion model an instability in the primary was amplified by the gravity of the secondary at periastron, hereby causing the eruption. The energy then comes from mass accreting onto the secondary, and the jets launched by the secondary shape the bipolar nebula. Many questions still remain, the most curious one is what instability was amplified. But despite of the unknowns, it is clear that the primary star could not have undergone this eruption without the help of the

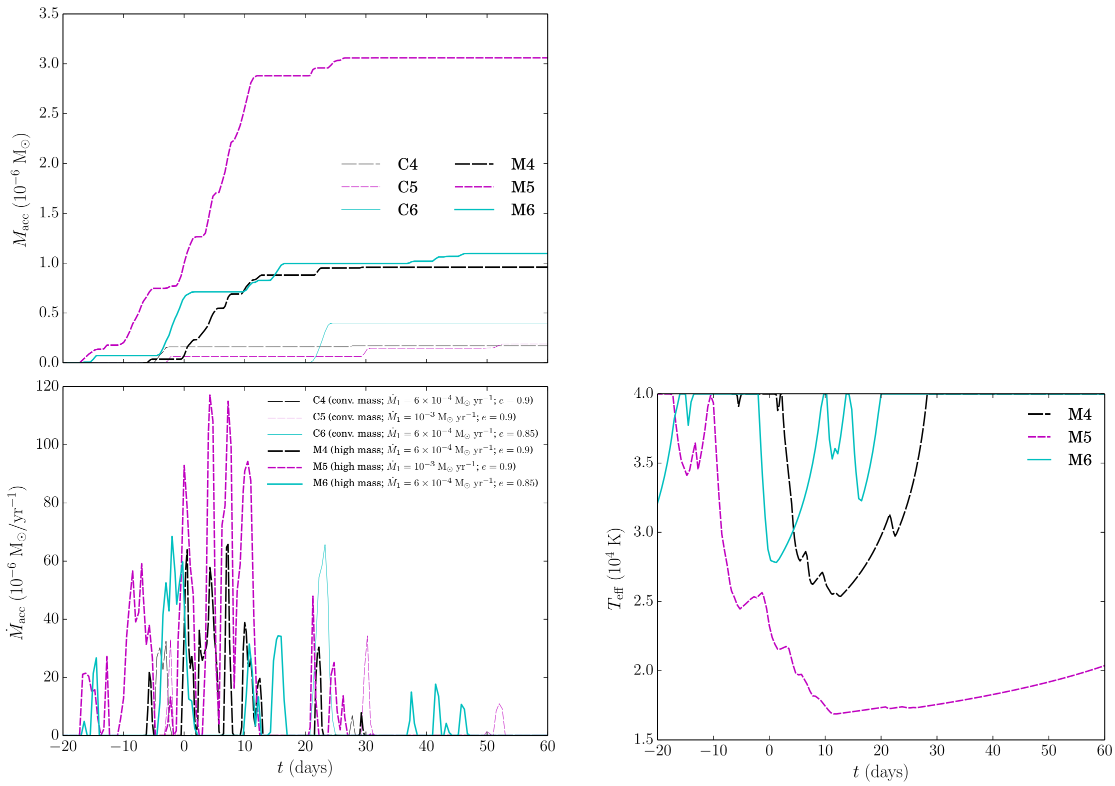

Fig. 2. Left: The accreted mass (upper panel) and the accretion rate (lower panel) for our simulations. Parameters are listed within the figure. It can be seen that for the high mass model (M-runs) much more mass is accreted onto the secondary. The main reason is the stronger gravity of the secondary. It is also very clear that a stronger mass loss rate of the primary (runs C5 and M5) causes a large increase in the accreted mass. The dependence on eccentricity is more complicated as lower eccentricity (runs C6 and M6) means larger periastron distance but also longer periastron passage. These two effects can combine in different ways, making the results difficult to predict. **Right:** The direction-averaged reduction in the effective temperature of the secondary.

secondary.

Accretion against ejected wind may seem to be a simple process, but in fact it is a problem with many fine details that requires a special code, careful parameter study, and high resolution simulations. The accretion may seem to be a small effect in one orbit, but in massive binary stars accretion is a process that may have a significant influence on the evolution of the stars, as the accreted massed can play a major role. For the duration of a few million years of evolution, a few $M_\odot$ can be transferred between the stars. The influence is significant both for the donor and the gainer, and both stars are expected to undergo a different evolutionary path than their single counterparts. As mentioned earlier, it also determines the stellar mass before collapse and consequently what kind of compact remnant will be formed. The effects of losing and especially gaining a lot of mass will be important for the next generation of stellar evolution codes, a generation that moves from using theoretical models that are parameterized and often simplified, to relying on results of advanced 3D simulations.

This work used the Extreme Science and Engineering Discovery Environment (XSEDE) TACC/Stampede2 at the service-provider through allocation TG-AST150018. This research was enabled in part by support provided by Compute Canada (`www.computecanada.ca`), thanks to the sponsorship of Prof. A. Skorek. We acknowledge PRACE for awarding us access to the national supercomputer Cray XC40 at the High Performance Computing Center Stuttgart (HLRS) under the grant number PrcPA4873/ipramkas. We acknowledge support from the Chairman of the Department of Physics in Ariel University, Prof. Y. Raichlin, and the R&D authority.

References

Akashi, M., Soker, N., & Behar, E. 2006, MNRAS, 368, 1706

Akashi, M. S., Kashi, A., & Soker, N. 2013, New A, 18, 23

Corcoran, M. F., Hamaguchi, K., Liburd, J., et al. 2015, in AAS Meeting Abstracts, Vol. 225, 344.15

Damineli, A., Hillier, D. J., Corcoran, M. F., et al. 2008a, MNRAS, 386, 2330

Damineli, A., Hillier, D. J., Corcoran, M. F., et al. 2008b, MNRAS, 384, 1649

Davidson, K. & Humphreys, R. 2012, ASSL, 384

Davidson, K. & Humphreys, R. M. 1997, ARA&A, 35, 1

Davidson, K., Ishibashi, K., & Martin, J. C. 2017, Research Notes of the AAS, 1, 6

Davidson, K., Ishibashi, K., Martin, J. C., & Humphreys, R. M. 2018, ApJ, 858, 109

Davidson, K., Martin, J., Humphreys, R. M., et al. 2005, AJ, 129, 900

Davidson, K., Mehner, A., Humphreys, R. M., Martin, J. C., & Ishibashi, K. 2015, ApJ, 801, L15

De Marco, O. & Izzard, R. G. 2017, PASA, 34, e001

Eldridge, J. J. 2017, Population Synthesis of Massive Close Binary Evolution, in Handbook of Supernovae (Springer), 671

Heger, A. & Langer, N. 2000, ApJ, 544, 1016

Heger, A., Woosley, S. E., & Langer, N. 2000, New A Rev., 44, 297

Kashi, A. 2017, MNRAS, 464, 775

Kashi, A. 2019, MNRAS, 486, 926

Kashi, A., Davidson, K., & Humphreys, R. M. 2016, ApJ, 817, 66

Kashi, A. & Soker, N. 2009a, New A, 14, 11

Kashi, A. & Soker, N. 2009b, MNRAS, 397, 1426

Kashi, A. & Soker, N. 2016, ApJ, 825, 105

Kudritzki, R.-P. & Puls, J. 2000, ARA&A, 38, 613

Madura, T. I., Gull, T. R., Okazaki, A. T., et al. 2013, MNRAS, 436, 3820

Mehner, A., Davidson, K., Humphreys, R. M., et al. 2015, A&A, 578, A122

Mehner, A., de Wit, W. J., Asmus, D., et al. 2019, arXiv e-prints, arXiv:1908.09154

Meynet, G., Ekström, S., Georgy, C., Chiappini, C., & Maeder, A. 2009, Reviews in Modern Astronomy, 21, 97

Moffat, A. F. J. & Corcoran, M. F. 2009, ApJ, 707, 693

Nielsen, K. E., Corcoran, M. F., Gull, T. R., et al. 2007, ApJ, 660, 669

Okazaki, A. T., Owocki, S. P., Russell, C. M. P., & Corcoran, M. F. 2008, MNRAS, 388, L39

Parkin, E. R., Pittard, J. M., Corcoran, M. F., & Hamaguchi, K. 2011, ApJ, 726, 105

Parkin, E. R., Pittard, J. M., Corcoran, M. F., Hamaguchi, K., & Stevens, I. R. 2009, MNRAS, 394, 1758

Pittard, J. M. & Corcoran, M. F. 2002, A&A, 383, 636

Puls, J., Vink, J. S., & Najarro, F. 2008, A&A Rev., 16, 209

Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444

Soker, N. 2004, ApJ, 612, 1060

Soker, N. 2005a, ApJ, 635, 540

Soker, N. 2005b, ApJ, 619, 1064

Teodoro, M., Damineli, A., Arias, J. I., et al. 2012, ApJ, 746, 73

van den Heuvel, E. P. J. 2017, Supernovae and the Evolution of Close Binary Systems, in Handbook of Supernovae (Springer), 1527

Vink, J. S., Heger, A., Krumholz, M. R., et al. 2015, Highlights of Astronomy, 16, 51

Vishniac, E. T. 1994, ApJ, 428, 186