Catching Stellar Mergers at Work with the Very Large Telescope Interferometer

Florentin Millour[1]
Eric Lagadec[1]
Orsola de Marco[2]
Dipankar P. K. Banerjee[3]
Djamel Mékarnia[1]
Alain Spang[1]
Olivier Chesneau[1†]

[1] Laboratoire Lagrange, UMR 7293, Univ. Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, Nice, France
[2] Department of Physics & Astronomy, Macquarie University, Sydney, Australia
[3] Astronomy & Astrophysics Division, Physical Research Laboratory, Navrangpura, India

The two Very Large Telescope Interferometer (VLTI) instruments AMBER and MIDI were used to study the close environment of two post-merger stellar systems: the R Coronae Borealis star V854 Cen and the red nova V838 Mon. The observations reveal the presence of flattened dusty structures in the core of both objects, which are very likely discs. This finding confirms that the merger of two stars can lead to the formation of a disc.

With the advent of optical interferometry, the close environments around many evolved stars have been resolved (see Chesneau, 2011). Companions encompassing a large range of mass, from stellar objects to Jovian-mass planets, are suspected to strongly influence the ejecta when a low- to intermediate-mass star reaches the asymptotic giant branch, or even as early as the red giant branch (de Marco, 2009). This interaction can potentially influence dramatically the fate of the star, leading to poorly known evolutionary paths, affecting the timescales of the different stellar evolutionary stages, to the extent that the product bears little similarity to, for example, the timescale and chemistry involved for the evolution of a single, naked star (Frankowski & Jorissen, 2007).

Interferometry in the near- and mid-infrared is the best tool with which to probe the close environment of evolved stars. Indeed, ultra-sharp images of these environments can be made, probing the inner hundreds of astronomical units, exactly where discs and companions occur and are intimately related to the evolution of the stars. Interferometry is ideally suited to resolve discs in the core of nebulae around stars of a range of masses from low to high. Here we present a snapshot of two such objects — the R Coronae Borealis (RCB) star V838 Cen and the eruptive variable V838 Mon — highlighting the seminal contribution of the astronomer Olivier Chesneau, who passed away earlier this year.

The R Coronae Borealis stars are hydrogen-deficient carbon-rich supergiants, best known for their spectacular declines in brightness at irregular intervals (De Marco et al., 2002). Two evolutionary scenarios have been suggested for producing an RCB star: a double-degenerate merger of two white dwarfs (WD) or a final helium-shell flash in a planetary nebula central star. V854 Cen has a large hydrogen content and polycyclic aromatic hydrocarbons (PAHs) detected in the mid-infrared, making it an unusual member of its class. This star also has a fast wind which reaches several hundreds of km s^{-1} (Clayton et al., 2013; Kameswara Rao & Lambert, 1993). Kameswara Rao & Lambert (1993) provided strong arguments that V854 Cen may be surrounded by a bipolar nebula, extending up to about 2 arcseconds, as revealed by its C II extended emission (Clayton & Ayres, 2001).

V838 Mon is a nova-like object that erupted in 2002 (reaching $V = 6.8$; Bond et al., 2003). The eruption was unlike classical novae because the effective temperature of the object dropped and the spectral type evolved to that of a very late L-type supergiant (Loebman et al., 2014). The mid-infrared flux of V838 Mon increased by a factor of two between 2004 and 2007, suggesting that new dust was forming in the expanding ejecta of the outbursts (Wisniewski et al., 2008). The expanding ejecta engulfed a companion close to the central source (Bond, 2006), seen as a faint, blue component in the spectrum, and Tylenda et al. (2005) argued that the pre-outburst spectral energy distribution (SED) is well matched by a pair of early main-sequence stars (B3V + B1.5V or B4V + A0.5V), making V838 Mon a triple system (main star + subsolar merging star + B3V companion). The 2002 eruption has been interpreted as the merger of a star of ~ 8 $M_\odot$ with a subsolar mass star (Tylenda & Soker, 2006).

V838 Mon is embedded in a dense, large-scale environment that was lit up by the light echoes resulting from the 2002 eruption (Bond et al., 2003), and potentially contaminates observations of the central star. High angular resolution studies with a small field of view of a few arcseconds are an asset in isolating the central regions from the extended dusty cloud. A great advantage of optical interferometry studies is thus to isolate the measurements from the extended environment.

Observations

VLTI observations of both targets were obtained with the low spectral resolution mode of AMBER ($R = 35$), the three-telescope combiner (Petrov et al., 2007). The observations were performed with the 1.8-metre Auxiliary Telescopes (ATs) using the compact (baseline, B ≤ 35 m) and long configurations (B ≤ 140 m). Full details can be found in Chesneau et al. (2014a) for V854 Cen and Chesneau et al. (2014b) for V838 Mon. Near-infrared observations were obtained with AMBER, similar to those for R Corona Borealis, using three ATs and the compact baselines. Mid-infrared interferometric data were also obtained for V838 Mon with the two-telescope recombiner MIDI (Leinert et al., 2004), which had a field of view ~ 0.3 arcseconds, identical to the near-infrared field of view, thanks to the use of the Unit Telescopes.

V854 Cen was also observed with the mid-infrared imager VISIR (Lagage et al., 2004) with a pixel scale of 0.075 arcseconds and field of view of 19.2 by 19.2 arcseconds through the SiC filter (λ = 11.65 µm, width 2.34 µm). Figure 1 displays the VISIR image, showing a clearly extended nebulosity around the central star.

Modelling the visibilities

The interferometer data do not directly provide an image of the sources, and we used an in-house tool called fitOmatic

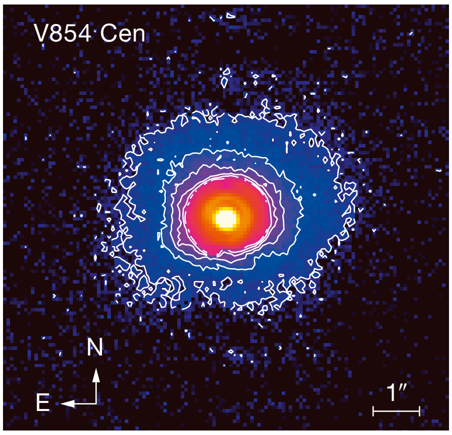


Figure 1. A VISIR 11.65 μm image is shown of V854 Cen with enhanced contours of the outer regions. The extended nebulosity can be seen in blue and purple.

(Millour et al., 2009) to fit simple geometric components. These fits provide the poor man's images displayed in this article (Figures 2 and 3), at an unmatched spatial resolution. The fitOmatic tool uses a set of simple (uniform disc, Gaussian, etc.) and less simple ("pinwheel", rotating and expanding disc, etc.) chromatic models that can be combined together to form more complex objects. The model is matched to the data using least squares, with special care taken for the phases (closure phase and differential phases). In order to fit the interferometric data (i.e. minimise the least squares), it uses a simulated annealing algorithm, leading to the best-match solutions shown in this paper.

V854 Cen

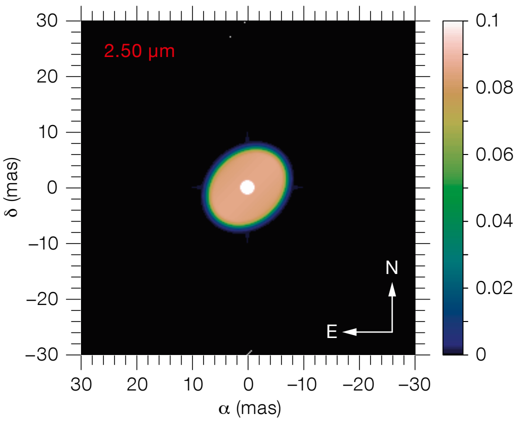
The best-match model for the compact array data has two components: an unresolved uniform disc (Θ < 2.5 milliarcseconds [mas], star component), and a flattened Gaussian (shell component) with a full width at half maximum (FWHM) of the minor axis of 8 ± 1 mas, and major axis 11 ± 3 mas. The orientation of the major axis is 126 ± 29° (Chesneau et al., 2014a). The long-array data shows that the star is unresolved (Θ < 1.0 mas). Figure 2 shows the fit of the AMBER data by the geometrical model.

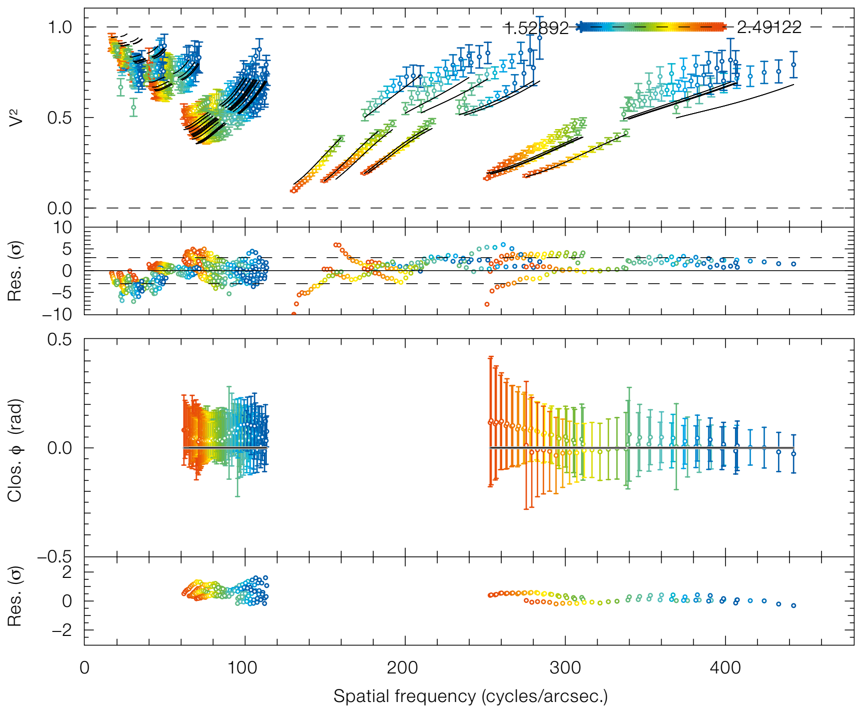
Given that the closure phase signal observed on V854 Cen is null within the error bars, a companion star, if any, would not have a flux exceeding 3 % of the total flux, i.e. well below the detection limit down to a typical spatial resolution of 10 mas. A model with a fully clumped uniform shell that contained up to 30 clumps was used to determine whether the high *H*-band visibilities could be explained this way, and indeed it does. However, such a model contains too many components and can only be loosely constrained. The position angle (PA) of the outer contours of the VISIR 11.65 μm images is only marginally consistent with that derived with AMBER, so it is possible that the spatial structure of the mass loss of V853 Cen is inhomogeneous and randomly variable.

V838 Mon

The MIDI dispersed visibilities were translated into the simplest possible geometrical *ad hoc* model — a Gaussian brightness distribution, as described in Leinert et al. (2004). The resulting fits shown in Figure 3 depict the general appearance of the mid-infrared structure. The semimajor and semiminor axes of the drawn ellipses represent the half-width at half maximum of the Gaussian. The extent of that structure increases from a FWHM of 25 mas at 8 μm to 70 mas at 13 μm, with a high flattening ratio. The major axis is oriented at a PA close to 10 ± 30°. The 2013 short-baseline AMBER visibilities are all very close to unity in the band centres at 1.7 μm and 2.2 μm and are consistent with a completely unresolved object. The

Figure 2. Bellow: Geometrical models from fitOmatic of the environment of V854 Cen at 2.5 μm. Upper right panel: Combined *H*- (blue) and *K*- (red) band interferometric visibilities obtained with AMBER compared with the signal from the polychromatic geometrical modelling. Lower right panel: Closure phases in the *H*- and *K*-bands plotted with the same colours.





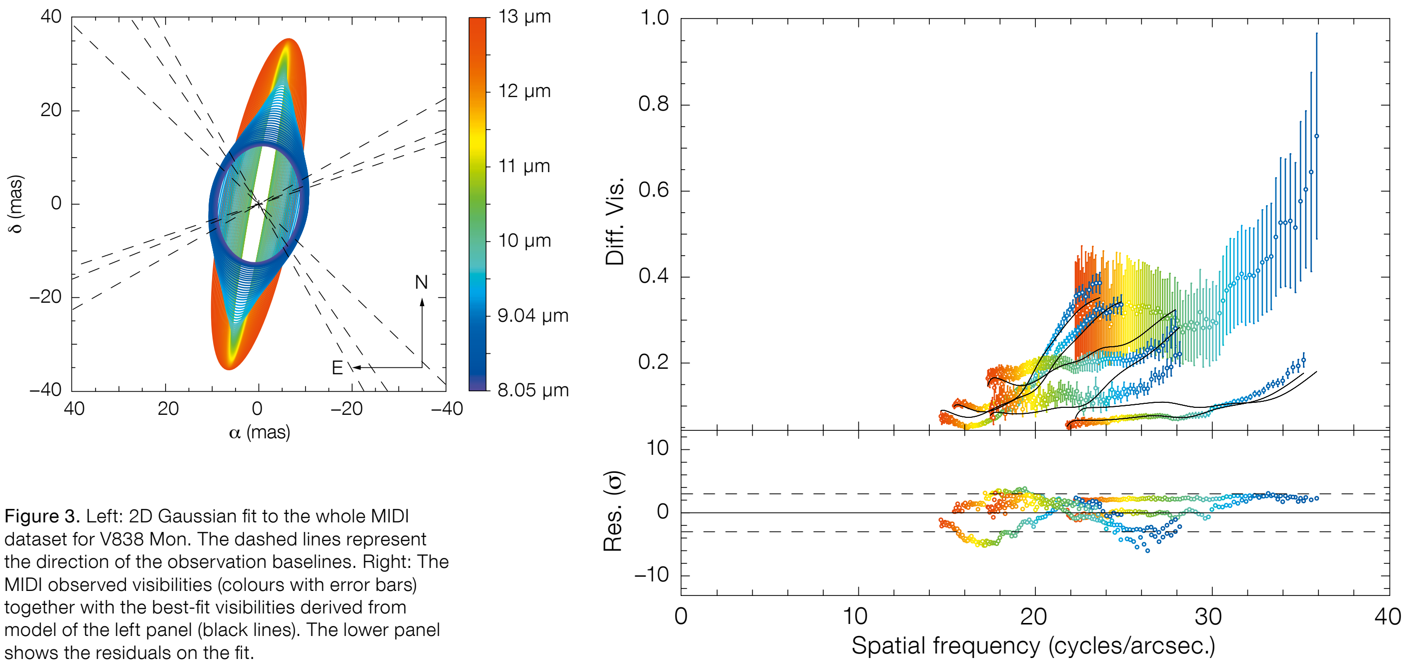


Figure 3. Left: 2D Gaussian fit to the whole MIDI dataset for V838 Mon. The dashed lines represent the direction of the observation baselines. Right: The MIDI observed visibilities (colours with error bars) together with the best-fit visibilities derived from model of the left panel (black lines). The lower panel shows the residuals on the fit.

visibilities as a function of wavelength of the *H*- and *K*-bands decrease relative to the band centres (1.7 µm and 2.2 µm) indicative of an object whose shape changes as a function of wavelength.

We again used the fitOmatic package to derive an angular diameter assuming a uniform-disc model around 2.2 µm. A diameter of 1.15 ± 0.20 mas was found, significantly smaller than that published by Lane et al. (2005). Since the AMBER closure phases are all equal to zero within the error bars, we can constrain the flux of a hypothetical companion star in addition to the central merger. Our conclusion was that there is a difference of at least 4 mag between the primary and the companion. The AMBER observations do not exclude the presence of the companion, but place important constraints on its near-infrared contribution to the spectral energy distribution.

Implications

V854 Cen

A moderately flattened dusty environment around V854 Cen was discovered from the VLTI AMBER observations. This sheds new light on the evolutionary scenarios that have been suggested for the production of RCB stars: the double-degenerate merger of two white dwarfs, which may lead to an axis of symmetry that promotes equatorially enhanced mass-loss and discs, or the final helium-shell flash in a planetary nebula central star, which may retain a central symmetry and promote no disc (Clayton et al., 2011).

The evidence for distributed dust emission suggests a disc that is possibly the relic of a past event, or that the observed spatial distribution reflects a field of randomly launched clumps in free fall around the central star, perhaps constantly replenished by the central star. Comparison can be made with the Be stars (Rivinius et al., 2013), for which the fast rotation of the central star together with its pulsational properties triggers the formation of a dense circumstellar disc. The RCB stars are known to be slow rotators, and the emission lines of V854 Cen are unresolved (≤ 20 km s^{-1}; Kameswara Rao & Lambert, 1993). V854 Cen has a well-known single-pulsation period (43.2 days) whose phase is related to the formation of the dust (Crause et al., 2007). Convection may also contribute to the launching process of the dust clumps, as in cool supergiant stars.

The polarisation properties of V854 Cen are similar to (albeit weaker than) those of the intermediate-luminosity red transient (ILOT) V4332 Sgr (Kaminski & Tylenda 2013). ILOTs are outbursts with energies intermediate between those of novae and supernovae, examples of which are V838 Mon. If the merger scenario for the RCBs applies, then they too may be in the ILOT range if observed at the time of the merger. Two 0.5 $M_\odot$ WDs will deliver quite a substantial amount of gravitational energy (≤ 5 × 10^{49} ergs), more than would be the case for a main-sequence star merger, therefore they may cluster in the upper region of the ILOT locus on the energy–time diagram. The stellar expansion that results would make the object a giant, as is the case for ILOTs.

V838 Mon

The size of the dusty flattened structure discovered by MIDI around V838 Mon is distributed between 150 and 400 au from the star. This is also in fair agreement with the spectropolarimetric measurements reported by Wisniewski et al. (2003) interpreted as scattering by a disc with a major axis at a PA of 37°. The supergiant has decreased in angular size by ~ 40 % in around ten years since the measurements of Lane et al. (2005). The linear radius is now estimated to be 750 ± 200 $R_\odot$ (3.5 ± 1.0 au) and the diameter decrease means the star's photosphere has shrunk during the intervening period at an approximate rate of 1 km s^{-1}.

The most likely hypothesis is that the flattened structure is simply the relic of the large dust formation event that was a consequence of the merging of the two stars (Wisniewski et al., 2008). The ejecta velocity was low at the time of outburst — less than 200 km s^{-1} — as derived from P-Cygni profiles by Lynch et al. (2004). In the ten years since the outburst, ejected material would not have travelled beyond 400 au. The picture revealed by interferometry of V838 Mon as of today is the following: it is now slowly becoming an anonymous red supergiant, surrounded by a flattened, probably transitory, dusty environment extending up to several hundreds of au.

Conclusions

The VLTI is the ideal tool with which to study such objects, thanks to its very high angular resolution. These observations have enabled us to study the close circumstellar environment of post-merger stellar systems. The observations of V838 Mon and V854 Cen confirm, for the first time directly, that the merger of two stars can lead to the formation of a disc.

This work has implications for the formations of bipolar nebulae. Indeed the presence of dense material close to the equatorial plane of the systems decelerates a wind or a fireball in these directions, leading to a bipolar outflow. These disc-like structures could also affect dust evolution, as dust evolves differently in a cooler and denser environment (disc) than the surroundings.

Remembering Olivier Chesneau

The work described here forms the final published work of Olivier before he passed away. He wrote the two papers describing the VLTI observations of V854 Cen and V838 Mon while he was in hospital.

Olivier Chesneau made wide-ranging contributions to the VLTI and high resolution astronomy. His results were widely publicised and he was awarded the 2012 Michelson Prize of the International Astronomical Union and the Mount Wilson Institute for major contributions in stellar astrophysics made with long-baseline interferometry. He was directly involved in the MIDI instrument and, through many observing programmes, with AMBER. He was part of the VLT SPHERE Guaranteed Time Observing programme and was involved with the second generation VLTI MATISSE instrument consortium. He also worked in the Jean-Mariotti Center (JMMC) as Principal Investigator of the Calibration Group. Olivier organised the VLTI school in Porquerolles in April 2010 and was a co-organiser of the interferometry school in Barcelonnette in the autumn of 2013. His enthusiasm, curiosity, and passion will be missed by many.

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Hubble Space Telescope Advanced Camera for Surveys (ACS) image of the light echoes around V838 Mon observed in 2004, two years after the outburst. Broadband ACS images in F435W (*B*), F606W (*V*), F814W (*I*) were combined for this colour composite. See heic0405a for details.