Evaluation of the Thesis: "The circumstellar environment in V838 Monocerotis: An interferometric view". PhD Candidate: Muhammad Zain Mobeen

The PhD thesis of Muhammad Zain Mobeen presents an extensive and in-depth study on the expanding environment of the Galactic Luminous Red Nova (LRN) V838 Mon. The study aims at reconstructing the configuration of the different circumstellar gas/dust components of V838 Mon making use of interferometric observations. This approach has already provided excellent results in gaining information on the structure of expanding nebulae in the Galaxy.

The thesis has a clear and coherent structure: it first provides a basic overview on the interferometry theory and techniques. This part is followed by an introduction on the LRN phenomenon (with emphasis on Galactic events), and finally a wide part is devoted to the candidate's original research work on the circumstellar environment (CSE) of V838 Mon.

Introductory part

The introductory part of the thesis has the following structure: in Chapter 1, basic principles of interferometry are illustrated, followed in Chapter 2 by basic information on the facilities and a detailed description on the baseline configurations adopted. A general overview on the image reconstruction techniques is in Chapter 3. Chapter 4 gives an introduction on the LRN phenomenon, a specific description of V838 Mon following the outcomes of the literature, and presents the evolution of its progenitor system up to the 2002 eruption, discussing the merging scenario. Chapter 5 reports previous interferometric studies of V838 Mon based on interferometric techniques that provided approximate constraints on the geometric structure of the post-outburst CSE. These articles from the literature have been used as references for the original work of the PhD candidate.

Reviewer's comments and concerns

Both the technical description (instruments used, tools, codes and image reconstruction techniques) and the scientific context (the concept of LRN and the overview on the state of our knowledge of V838 Mon) have been synthetically but fairly comprehensively described in the first part of the thesis.

However, a few additional figures would have been appreciated to support the textual description. Some examples: a figure showing the spectral evolution of V838 Mon over the time; or the long-term light curve of the LRN to emphasize the emerging contribution of the blue companion star in the observed light curve, or even the photometric signs of its eclipse in late 2006 (e.g., Fig. 1 in Munari 2007, A&A, 389, L51). While this is detailed in the text, the lack of supporting figures is evident.

As an additional note, when Intermediate Luminosity Optical Transients (ILOTs; Sect 4.0.1) are introduced, there is an incorrect statement: "ILOTs fainter than $M_V \sim -10$ are collectively called Luminous Red Novae." This is formally incorrect, because numerous ILOTs fainter than -10 mag are known without being necessarily LRNe (e.g., LBV-like outbursts o other flares of massive stars). In addition, we are aware of a number of extra-galactic LRNe that are extremely luminous (up to -15.5 to -16 mag; see Table 4 in Pastorello et al. 2021, A&A, 671, A158). The existence of intrinsically luminous extra-galactic LRNe, that are more frequently discovered than the fainter Galactic counterparts, has been reported only as a marginal note.

Minor correction: at page 11 (Chapter 2.0.1) there is an unprocessed reference to "Fig.??"

Research articles

The core of the dissertation, which comprises two articles published by A&A and one submitted, is an original attempt of reconstruct the V838 Mon environment using interferometric techniques. The contribution of the candidate's research can be summarized as follows:

1. **Publication 1 (Mobeen et al. 2021, A&A, 655, A100)** provides an attempt to resolve the LRN environment using interferometric L-band data taken in 2020 with VLTI+MATISSE. Simple models were used to fit the observables, and the best-fit models supported an environment with a long-lived elongated structure oriented at a position angle (PA) of −40 deg. This study does not reveal new features in the V838 Mon environment. However, as an important outcome, the reconstructed CSE structure partly overlaps those observed in the past with other instruments in the infrared and millimeter domains, implying they are manifestations of the same emitting region (such as a dusty disc or a torus). In brief, the main outcome of this study is the confirmation of the elongated structure of the V838 Mon CSE.

2. **Publication 2 (Mobeen et al. 2024, A&A, 686, A260)** is probably one of the most detailed and complex interferometric studies of V838 Mon. A new set of multiband interferometric data obtained with different instruments is used to resolve the LRN environment. Geometrical models of observed visibilities and closure phases from infrared (JHLM) data confirm the existence of stable elliptical feature (likely a disk) oriented at PA -40 deg in north-west direction, as suggested in the first paper. The presence of CO and water features is also revealed from the K band spectra. However, geometrical modelling of the N-band observables indicates a distinct emitting region (oriented at a different PA, and elongated in the north-south direction). Observations collected from 2020 to 2022 are combined to allow image reconstruction of V838 Mon. The K and (even more) H band reconstructed images reveal a non-homogeneous by-polar outflow, with a southern lobe aligned with the elongated feature at PA −40 deg, while the H-band northern lobe is oriented at a different PA than the above structure. These outflows are interpreted as possible jet-like features (expected in mergers), which survive as bipolar clumpy outflows years after the coalescence. In brief, this second paper enters more in detail into the structure of the V838 Mon CSE, providing indisputable proofs of a large asymmetry (and possibly clumps) in the LRN ejecta, supporting the idea that beamed outflows are common in LRNe.

3. **Publication 3 (Mobeen et al. 2025, submitted)** investigates the physical nature of the dusty medium in the proximity (10-300 AU) of the merger making use of the H and K band observation presented in Publication 2, and modelling the data with a radiative transfer code (RADMC3D). The H and K band simulated images for the best model indicate a survived merger embedded within an inner dusty ellipsoid whose major axis extends up to 3 mas, while the main feature is a torus constrained from 3 to 5 mas. Simulated H band squared visibilities and closure models require the inclusion of a jet nearly perpendicular to the torus. The reconstructed scenario matches the expectations for a post-merger evolution: the torus is what survives of the original accretion disc around the primary, while the launched jets are expected to interact with the CSE favouring the formations of clumps and other fine substructures to be explored with higher resolution future observations. One of the main outcomes of this work is the prediction that these circumstellar components are transitional, and major dynamical changes will likely occur in the future. The paper finally speculates on the the future evolution of the V838 Mon merger as a blue struggler.

Reviewer's comments and questions

The above publications constitute coherent and incremental progresses towards our comprehension of the structure of the V838 Mon CSE, providing new arguments to support the stellar merger scenario for this LRN, and to predict future evolution of the system. The research published by the candidate substantially confirms past observations and theoretical predictions, but provides much more details on the overall structure of the V838 Mon CSE. This study is a milestone for future observational studies based on new interferometric and polarimetric data of V838 Mon, but also for other Galactic LRNe.

Questions for the candidate:

1. Rough information is available on the asymmetries and clumps revealed by the near-infrared observations and modelling. Any strategies could help us to resolve much more in detail the structure of the different circumstellar components of V838 Mon? Fine tuning the observational strategies (e.g. adopting longer baselines, longer exposure times), or using new and more complex models, or next-generation instruments are necessary for major progresses in this direction?

2. The candidate has briefly mentioned in the Thesis the existence of extra-galactic LRNe. LRNe show variety of observables (intrinsic luminosity, the duration of the eruption). Five order of magnitudes separate the faintest Galactic events (V4332 Sgr and V1309 Sco) from the brightest extra-galactic LRNe. This is primarily due to the large range of stellar masses involved: the faintest galactic LRNe have a primary of $\sim$1 $M_\odot$; V838 Mon (as well as some LRNe in M 33) have primaries of 8-10 $M_\odot$; brightest and distant LRNe originate from primaries of dozen $M_\odot$.

   - Does the candidate expect significant differences in the structure and the configuration of the CSE produced by merging systems with masses largely different from that of the V838 Mon progenitor? The differences are only due to the masses involved or may other parameters play an important role?
   - Due to their distance and modest apparent magnitudes, we cannot successfully apply interferometric techniques to resolve the environments of LRNe much more distant than V838 Mon. Are there other techniques to provide some (though rough) insights on the structure of the CSE of these events?

3. Studying a detail of an astrophysical transient is important, but it is crucial that this research can be placed in a broader context and compared with similar astrophysical phenomena. Has the candidate any research plans in this direction?

Summary

The Thesis is in general well organised, and - despite the complexity of the analysis made - it can be followed also by non-expert readers. V838 Mon is one the most interesting astrophysical transients discovered in the new millennium, and has been the subject of hundreds of publications. Former articles have proven the potential of interferometry in reconstructing the expanded structure of V838 Mon. This Thesis has the merit to fine-tune the strategies to expand our knowledge on the geometry of the material embedding the central star. Each publication based on interferometric studies of V383 Mon is a small but crucial progress to constrain the properties of the progenitor system and its remnant. For this reason, I can safely state that the dissertation constitutes an original solution to the proposed astrophysical challenge.

As a minor note, I would have appreciated if this in-depth study of V838 Mon had been discussed in a broader context, accounting for recent progress in the observations and modelling of LRNe.

While the statements of the coauthors emphasise their role mostly in the data reduction steps, the analysis of the data and their interpretation were the main part of the Ph.D. activity of the candidate, who demostrated a solid knowledge and control of this research field, as well as his ability in leading an independent scientific work.

Summing up, I consider the doctoral thesis of Muhammad Zain Mobeen to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Padova, 2025 August 20

Andrea Pastorello