Peer Review File

Manuscript Title: The complex circumstellar environment of supernova 2023ixf

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

A. Summary of the key results
Authors present an analysis on SN 2023ixf, one of the closest and most notable supernovae of the last several years. The study is based on a robust set of data including unique HST UV spectroscopy, which allows to temporally resolve the emergence and evolution of the SN emission from the earliest phases. The presented data and their analysis uniquely
provide a temporally-resolved description of a massive-star explosion, characterize the pre-explosion evolution of the doomed star, and demonstrate a method to directly measure the pre-explosion chemical composition of supernova progenitors.

B. Originality and significance
I find the results and conclusions to be original, significant, and immediate interest for the astrophysical community.

C. Data & methodology: validity of approach, quality of data, quality of presentation
Authors present a rich set of data including unique measurements (especially HST UV spectra). Collection and careful analysis of this large data set was an essential step in achieving the presented unique results.

D. Appropriate use of statistics and treatment of uncertainties
Basically, authors handle measurement uncertainties carefully. My only concern is that authors do not seem to take care of the uncertainty regarding the distance of the host galaxy. I suggest to give the proper value of the host galaxy distance reported by Riess et al. (Line 81) and to check how this distance uncertainty propagates into the calculated luminosity values (even its effect is probably not too significant). It'd be also fair i) to calculate the uncertainties of the distances of star forming regions from the SN location (in Lines 205, 251, 353, 712), or ii) to mark that these are only rough values (as did in Line 721).
Methods and results presented in this manuscript do not require the application of advanced statistical methods.

E. Conclusions: robustness, validity, reliability
I find the conclusions and data interpretation valid and reliable.

F. Suggested improvements

* I already mentioned above my concerns about the lack of handling the uncertainty of the host galaxy distance.

* I suggest to give a more detailed argument why approximating the shock velocity by the measured photospheric velocity is a correct step (Line 125). I do not see much more information about that in Methods $3 authors refer to. Authors could also refer to some theoretical works on this topic (e.g. Moriya+2011 and 2018; Kozyreva+2020, ...) here.
It'd be also useful to clarify the differences of photpspheric velocity and ejecta velocity (mentioned and assumed to be ~10,000 km/s, Line 204).

* Line 135: It's important to clarify that the mass-loss rate of ~0.01 M_sun/yr estimated by e.g. the cited authors (Jacobson-Galán et al.) pertains only for a very short (few years-long) period before explosion (and, in the work of J-G. et al., assuming a larger wind velocity of 50 km/s). Furthermore, it's important to note here that several groups have looked for and found no evidence on such pre-explosion outbursts in the receding 5-20 yrs (see e.g. Neustadt et al. 2023, Dong et al. 2023, Flinner et al. 2023).
As a connecting note, it is not clear for me how the authors estimate the total CSM mass of <0.01 M_sun (Line 153). Above, they give a mass-loss rate of ~0.01 M_sun/yr. So, are they assuming a very short timescale (<1 yr) of intense mass-loss here? But, in later parts of the text, they assume a much longer timescale (1e4-1e5 yrs).

* I find the text describes the estimations of the ejected and initial masses (Lines 387-394) a bit rough. First, authors mention that "... the measurements of ref40 are omitted, as they are both an outlier..." - it is not clear what kind of measurements the authors mean here. Second, all single initial masses can be found in the literature have quite large uncertainties, which also need to be taken into account before drawing conclusions.

G. References: appropriate credit to previous work?
In general, authors have striven for doing a fully comprehensive overview on both the general scientific background and the literature on SN 2023ixf available at the time of submission. Nevertheless, I miss some references I mention in other parts of my review. I also note that giving references as upper indices, or as "ref..." is weird to me - but I delegate this decision to the Editor.

H. Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions
I find both the abstract and the introduction clear and appropriate. Well, there is no 'Conclusions' or 'Summary' at the end of the main text.

I. Further specific comments to the authors

* Line 213: There is a bad reference.

* Line: 216: It seems to be unnecessary to resolve the word "SNe" (=supernovae) here.

* Line 385: v_env is not resolved and has not been introduced before.

* Line 683: It should be mentioned that SN 2010jl belongs to another type of SN explosions assumed to emerge from a very different progenitor star than 2023ixf.

* Fig. 3.: In the label of the upper x axis, if it' truly optical depth, then it has no units. If unit is correct, then it' not optical depth (but rather kappa).

As a conclusion, I find the manuscript to be well-written and coherent. I find the presented results to be significant enough to be published in Nature. I suggest the draft for being accepted after the authors address my concerns described above.

Referee #2 (Remarks to the Author):

This manuscript presents observations of the nearby core-collapse SN 2023ixf and their interpretations. Especially, it shows UV spectra from Hubble Space Telescope that are rarely available. Although the spectra are impressive and provide a lot of interesting information, I am not convinced that the manuscript provides impacts that are high and broad enough to be published in Nature. The basic picture of shock breakout in dense circumstellar matter (wind shock breakout) in Type II SNe has already been established well. The UV spectra provide new insights and additional evidence for the wind shock breakout, but what the authors found is not far from what has been expected.

I was not satisfied with the interpretations in the manuscript, either. In Line 114, the emission radius is set to be r_0 + v_s*t. However, shortly after the wind shock breakout, the shock is still in optically thick region and photons are released at photosphere R_ph until t ~ R_ph/v_s. Thus, we do not observe the shock radius (r_0 + v_s*t) directly. The early emitting radius is constant simply because we observe unshocked, static R_ph at first.

Several different v_s is assumed (e.g., Line 114 and Line 125). It is better to be consistent.

Line 124: t_rise should be R_ph/v_s.

Line 129: The conversion efficiency from kinetic energy to radiation is assumed to be 100%, which is too large.

Author Rebuttals to Initial Comments:

Referee reports:

Referee report 1:

We thank the referee for their detailed report and have addressed their suggestions fully

- Appropriate use of statistics and treatment of uncertainties:
    - The error estimate has been added to the cited distance from Riess et al. 2022
    - This distance error is negligible compared to the statistical errors on the BB luminosity, radius and temperature. We therefore omit it from our calculations. We also note that any such error will be applied to all data points equally and is therefore a systematic error.
    - References to the nearby H II regions has been removed as part of the removal of the chemical composition analysis
- Suggested improvements:
    - A paragraph explaining our reasoning for the use of measured photospheric as the shock velocity has been added to section 3.
    - The discussion on timescales has been expanded. We now explicitly state that the confined CSM originated from a recent (~few years) event, while the extended wind could have been emitted in a process lasting decades or much more.
    - We've added a paragraph to the main text highlighting our results on the remanent mass. We also revised the text of the aforementioned paragraph (Lines 387-394) to make it clearer.
    - References missing by the referee have been added.
- Further specific comments to the authors
    - Line 213: Fixed the bad reference.
    - Line: 216: Have pushed the introduction of the SN acronym to a later point.
    - Line 683: A short sentence explaining the context of SN2010jl and its comparison to a type II-P SN has been added.
    - Fig. 3.: Fixed the optical depth units to unitless as required.

Referee report 2:

We thank the referee for their report and would like to expand on the issues they brought up:

- Impact of the paper:

  While a shock breakout in wind has been studied in the past (e.g. Ofek et al. 2010) this has been done for type IIn SNe, which are characterized by their interaction with their CSM environment. What is new in our study is that we resolve for the first time a shock breakout in dense CSM of a regular type II SN, and distinguish it from what was theoretically expected from shock-cooling models.

  Importantly, combining our unique UV-optical dataset with X-ray data from the literature and XRT we map the CSM environment of SN 2023ixf in a novel way only from first principles.

  In fact, the X-ray data we present is the most extensive X-ray dataset of any SN type II. Understanding the hardness of the SN SED arising from its interaction with its surrounding CSM provides key explanations to several questions not answered before for any other SN:

    - What the source of the ionizing radiation producing the narrow flash-features is
    - Why do the flash-features increase in ionization between days 1-2
    - Why do flash-features persist for more than a week after explosion

  Additionally, we present in the final paragraphs a novel analysis showing for the first time how a combination of progenitor observations and the excellent supernova observations in hand can be used together to constrain the mass of the object that was left behind – which using current models has to be either a black hole or a very massive neutron star. Furthermore, a continued X-ray campaign could bolster this insight or else show that massive star evolution models need significant revision.

  We therefore disagree with the claim that our manuscript is not high impact and broad enough to be published in Nature. There is definitely “something additional” here in the insight into the remnant mass.

  To that end we also continued to observe X-ray data and have added 2 more XRT data points to the current revision.

- Further specific comments:
    - The paragraph containing Line 114 has been removed entirely in order to shorten the main text since it provided mostly introductory material.
    - The shock velocity has been fixed and is now consistent
    - Line 124: we define R_{BO} as the radius at which the photosphere is before breakout (tau~c/v) and it is therefore an alternative notation.
    - Line 129: The conversion efficiency is negligible since the shock is radiation-mediated throughout this phase it is very close to 100% efficient. Specifically, the amount of ~1eV photons released during the rise time from our luminosity measurements can be estimated as ~1e60 photons, while in a 0.1 solar mass shell of CSM exists 1e57 electrons. Thus the efficiency can be reduced by up to 0.1%.

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

Thank the authors for the improved text and that they carefully addressed and answered my comments. I suggest the draft for being accepted.

Referee #2 (Remarks to the Author):

I don’t have any further comments. The manuscript can be recommended for publication.