Peer review report

Title: The Crab Nebula's Secret Past: Analysis of the Historical Light Curve of SN 1054 and Implications for the Progenitor

Author: Catherine Petretti

Summary

The study focuses on determining the supernova type of the Crab Nebula (SN 1054) through analyzing its historical light curve. Three observations were collected from the medieval records and ranged from 1054 to 1056 (642 days). The author compares the light curve with those of 11 core-collapse supernova from the Open Supernova Catalog by calculating the reduced Chi-square value to find the best-fit. As a result, SN 1054's light curve agree bests with the supernova SN2004dj, which is type II-P supernova. The author went on to find the linear relationship between the total irradiated power over the 642-day time period with the progenitor mass of the supernova. Using the fitted linear equation and the total irradiated power of SN2004dj, the study determines the progenitor mass of SN 1054 to be 20 solar masses. However, its mass in literature is about 8-10 solar masses. Thus, the author argued that SN 1054 may have a higher irradiated energy than expected. The study also included a discussion about the core-collapse mechanism of the Crab Nebula, specifically examining if it is caused by the electron capture process (ECSN) or a Fe-core process (FeCSN). According to the literature, SN 1054 was an ECSN and type IIn supernova. However, the light curve of such type is too dim to fit the case of the Crab nebula. Thus, the author suggested that SN 1054 might belong to the FeCSN case. In the conclusion, the author emphasized that the amount of data points it not enough to make a conclusive statement about the type of the supernova, and further studies with sufficient data are necessary.

Recommendation: accepted with minor revisions.

Justification

a. Major points

- Introduction:
  - The author should include the definition of each supernova types mentioned in the paper (II-P, IIb, II-L, IIn, and IIn-P)
- Observation:
  - *"Photometric data were obtained … and II-L"*: Even though there are 11 light curves, there is only 1 for type II-b and 1 for type II-L? The author should discuss how this inequality does not create biases in the comparison.
- Methodology:
  - *"… to calculate a linear trend between logP_642 and logM_prog.""*: the author should explain how do we know that the relationship between the two variables are linear? (or if it is an assumption, the author should also state it).

- *"Using P_642 of SN 2004dj … an approximate progenitor mass for SN 1054."*: the author should explain why we don't use the known mass of SN 2004 but have to the linear trend?

- Discussion
  - *"Since the progenitor mass reported in this paper, 20 solar mass, … SN 1054 most likely has a higher irradiated energy than expected…"*: is the value of 20 solar mass a conclusion for the progenitor mass, or it just suggests a higher irradiated energy? The author should make it clearer.

b. Minor points

- Observation:
  - *"… to be 2 mag and 20 days …"*: justifications for choosing this error range.
  - *"Correcting for a distance of 2 kpc and visual extinction of Av = 1.6 mag …"*: needs citation or justifications.
  - *"These SN light curves as well as the SN 1054 historical light curve are displayed in Figure 1"*: it might be better if the author includes the magnitude of these historical data points in a table. This makes it easier for further studies to collect the data.

- Methodology
  - *"To determine which light curve best fit the SN 1054 historical light curve …."*: the author should state that the reduced Chi-square is used for comparison (instead of just using the notation of Chi-square), and that the best match will have the reduced Chi-square approximately to 1.
  - *"The resulting linear trend is … is shown in Figure 3."*: are there any other linear fits of the same relationship in the literature? If yes, the author should mention and compare them here.
  - *"... which is comparable to the known progenitor mass of SN 2007dj …"*: I think the author miswrote it from SN 2004dj to SN 2007dj.
  - Error bars for Figure 3 should be included, at least for the mass (x axis).

- Discussion
  - *"The SN 1054 progenitor mass is established from the literature to be 8-10 solar masses"*: the author should explain how this number was determined in literature? Also, are there any points that can help explain the difference between this value with the reported value of 20 solar mass?
  - *"The low kinetic energy of the Crab ejecta (~ 7e42 J)..."*: needs citation for this value.
  - *"... it is worth noting that all of the type IIn light curves … (excluding SN 1988Z)"*: according to Table 1, SN 1988Z is a type II-P supernova, why does it appear in the argument about type IIn light curves?
  - *"The main complication with adopting an FeCSN model, however, is the low Ni56 abundance in the Crab, which is typical for ESCNe*.": need citation.

- *"Smith (2013) suggested that SN 1054 is a type IIn-P…"*: the author introduces a new type here (in addition to the 4 types that are already discussed) but does not explain clearly what it is.
- *"such as the high neutron star kick of ~160 km/s."*: needs citation.

- Conclusions and future work
  - *"… than expected for the known progenitor mass of ~ 8 to 10 solar masses. In comparison with the light curve of SN 2008S, a type…"*: the author should have a transition between the two sentences and rephrase the second setence. The readers may not understand why the author wants to compare the light curve of SN 2008S while reading. For example, the transition can begin with the fact that SN 1054 was classified as type IIn ECSN in literature, and then states that it does not match the light curve of SN 2008, an example of such type.
  - *"However, by acquiring sufficient data…"*: if the author means the data for SN 1994W, SN 2009kn, and SN 2011ht, how can we have more data if those events already happened? If that is not what the author mean, the author should rephrase the sentences to make it clearer what data is mentioned.

Evaluation

The length of the paper is appropriate and the topic is appropriate for the journal. The abstract and the title convey the content of the study. The contribution to science is significant, but it only gives suggestion rather than a firm answer to the type of SN 1054 .The English in the paper is easy to follow, however, some citations are missing in the paper. The discussion section is a bit hard to follow because the study involves a lot of speculations, but overall it is well stated. Regarding the data management plan, the author should include the table showing the magnitude of SN 1054 that she collected (as mentioned in the justification section above).

All my comments are constructive reviews and sometimes they can come from personal preference or personal experience. Please understand if I misunderstand the author in some points. Also, please send my congratulation on the author's work and I enjoy reading the paper.

Author: Catherine Petretti

Title: The Crab Nebula's Secret Past: Analysis of the Historical Light Curve of SN 1054 and Implications for the Progenitor

Summary:

The goal of this paper is to determine the best fitting light curve type and progenitor mass for SN 1054. Historical data was used to recreate a light curve for the supernova consisting of three data points over 642 days. Next, photometry of 11 supernovae were obtained from the Open Supernova Catalog. The supernovae must have at least 642 days of photometry and reliable progenitor masses. The photometry was converted to absolute magnitudes and plotted along with the historical light curve. Chi^2 analysis was used to determine the best fit light curve. SN 2004dj has a Chi^2 of 1 and was selected as the best fit. Next, the irradiated power for each supernova in the 642-day time period (P_{642}) was calculated and plotted versus the progenitor mass. The log P_{642} vs progenitor mass displayed a linear relation. Using the linear trend and the irradiated power of SN 2004dj, the progenitor mass of SN 1054 is determined to be 20 solar mass. From this study, it is determined that SN 1054 is most likely a type II-P supernova and the result of Fe-core collapse.

Rating: Accept with Minor Revision

Minor Revisions:

- Introduction, second paragraph: The sentence staring with “Despite ongoing observations and investigations …” is hard to parse and should be re-written or broken into two sentences.
- In the introduction, page 2, is ECSNe and FeCSNe different types of supernovae or is the added ‘e’ at the end a mistake? This appears multiple times throughout the paper.
- In equation 1, in the formula for the K-correction, is the *z* term redshift?
- In section 3, where does the value for L_0 come from? Is this a universal constant or specific to the supernova?
- The analysis demonstrates a linear relationship between log P_{642} and log M_{prog}. Is there a known relationship between irradiated power and progenitor mass? Was this expected through relationships established in the literature or was it discovered in this study?

Major Revisions:

- The selected supernova, SN 2004dj does not have the lowest chi^2 value. Why was this supernova chosen over SN 1993J and SN 2004et which have the lowest chi^2 values? Through inspection of Figure 1, SN 1993J and SN 2004et meet all three error ranges while SN 2004dj does not meet the final error range. It is unclear why SN 2004dj was selected when two other supernovae seem like better selections.

Evaluation of Criteria:

Is the length appropriate?

- Yes

Are the title and abstract sufficiently informative?

- Yes, the title is catchy and informs the reader of the topic. The goals of the paper and results are displayed in the abstract

Is the contribution to science significant?

- Yes, however, the drawback is that the results are inconclusive due to the lack of data points in the historical light curve. The results that are obtained which help unveil the true nature of SN 1054 and the creative use of historical data give scientific merit to this paper.

Is the level of English adequate?

- Yes

Is the literature properly cited?

- Yes, the background presented is rooted in literature. All values obtained from previous studies are properly cited

Are the results clearly and accurately presented?

- Yes, the historical light curve is presented in a figure and the numerical results are displayed in a table.

Is the topic appropriate for this journal?

- Yes

Data Management Plan

- All results are clearly presented in figures or tables. The qualitative results pertaining to the supernova type and progenitor type are discussed in section 4.

Additional Comments:

- I found this paper extremely interesting and enjoyable to read. I would like to thank the author for all their hard work in producing this study. I love the creative use of historical data to produce a light curve of SN 1054. I think this paper represents an important historical standpoint to the dispute on the progenitor mass and supernova type of SN 1054.

Note to the Editor – Catherine

To the Editor-

I stand by my review of this paper. You are free to disclose my identity to the author, should they request it. Other than my worry that the introduction section does not adequately explain the topic of research, I have not found major fault with anything else. In light of the drastically different calculated progenitor mass for SN 1054 than is currently accepted, I would recommend the publication of this paper in order to widen the perspective on the nature of SN 1054.

Best regards,

Danielle Mortensen

Catherine Review

Summary:

The author conducts a study of SN 1054, now seen to be the Crab Nebula. They use three historical data points of the supernova brightness to create a lightcurve and then compare it to more recent supernovae. Using several other supernova lightcurves, they were able to find a numerical relationship between the irradiated power and the progenitor mass. By fitting the best comparable supernova lightcurve (SN 2004dj) to SN 1054, they were able to determine, with the power-mass relationship, the approximate mass of SN 1054's progenitor. This mass was determined to be 20 solar masses. This is different from the accepted value of ~8-10 solar masses, and the author considers this and concludes that SN 1054 was likely a type II-P (iron-core collapse) supernova from a low-mass red supergiant. The author also discusses the possibility that SN 1054 was an electron-capture supernova.

Recommendation:

I would recommend that this paper be **accepted with minor modifications**.

Justification:

- *Major Points:*
    1. Author does not explain different supernova types in introduction.
        - Unclear what the different supernova types (core collapse and electron capture) are and what their differences are
        - Unclear if the labels (II-P, IIn-P) are related to core collapse and electron capture SNe
        - An explanation of these may give the reader more resources to come to their own conclusions about the SN type from the data presented
- *Minor Points:*
    1. Section 2: "…had an apparent brightness comparable to Venus in the night sky…"
        - Perhaps worth addressing whether or not things like light pollution and other important factors which would have changed perception of brightness 1000 years ago were taken into account with these data points
        - "…suggesting an apparent magnitude of mv ~ 6 mag." → would this standard have been true that long ago?
    2. Section 2: "…error bars were assumed to be 2 mag and 20 days."
        - Why did we assume these?
        - Are they arbitrary or was there a process to choosing these numbers?
        - Also may be good to specify that these are the errors in each direction and not the total range of error
    3. Section 2: "(2) a well-established progenitor mass…"

    - What constitutes "well-established"? Especially if you are proposing challenging this progenitor mass to be 20 solar masses instead of 8-10 solar masses
4. Section 4: "The SN 1054 progenitor mass is established from literature to be ~8-10…"
    - Perhaps worth explaining why this is the accepted mass and why everyone has come to these conclusions if you have concluded differently
5. Section 4: "…Table 1 yield the most deviant chi squared values (excluding SN 1988Z)…"
    - Why are we excluding this? Is it important/have significance?

Evaluation:

- *Is the paper length appropriate?*
    - Perhaps more explanation of supernova types should be included which would make the current paper version a little shorter than need be to properly introduce the audience to the topic.
- *Are the title and abstract sufficiently informative?*
    - Yes! Wonderfully put title and abstract. They both present the results gained by this analysis but also keep the door open for further interpretation and evaluation of the true nature of SN 1054.
- *Is the contribution to science significant?*
    - Yes. Quite significant if this is a truly notable challenge to SN 1054's widely accepted progenitor mass.
- *Is the level of English adequate?*
    - Yes. Easy to read and understand.
- *Is the work properly grounded in literature?*
    - Yes. Good notable mention of other works which have suggested opposing views to the conclusions of this research, but author still adequately defended their conclusion.
- *Are the results clearly and accurately presented?*
    - Yes. The resulting conclusion of SN 1054 likely being a type II-P is made quite clear while not ignoring the thought that these results are subject to change.
- *Is the topic appropriate for the Journal?*
    - Yes. The author's research is a clear fit for this Journal on the topic of supernova analysis.
- *Is the data management plan good?*
    - Yes. The author clearly states their data points, errors, and methodology making this research fully repeatable and accessible to the public.

Final Comments:

This is a wonderful paper with the potential for great implications and importance in the field of supernova analysis and uncovering the past of the Crab Nebula. I hope these comments are

accepted as constructive criticisms and the author finds them helpful. My best wishes in their success!

Summary:

> This paper describes an analysis of the supernova remnant SN 1054, the Crab Nebula. Using observations from historical data, a light curve was generated in the V-band absolute magnitude. Photometric data from the Open Supernova Catalog was corrected to the same scale and overplotted on the Crab light curve. χ^2 was calculated for each with regard to their fit of the Crab data. The curve with the best fit (SN 2004dj) was chosen to represent the Crab data. This curve was converted to luminosity and then integrated to obtain the total irradiated power. Using this, the progenitor mass was inferred to be 20 solar masses. The paper then goes on to compare the results to those of previous literature and makes the suggestion that the Crab is a type II-P from the Fe-core collapse of a low-mass red supergiant.

Recommendation:

> Accept with minor revision

Points of Consideration:

Major:

> Mass value does not have error bars or an appropriate mass range

Minor:

> For the 3rd inference in §2, an explanation of why magnitude 6 is considered invisible would be beneficial
>
> Figure 1: the black data points get lost in the other light curves
>
> Author could why are the chosen error bar assumptions made in §2 valid (20 days and 2 mag)
>
> §3 ¶2 could have the linear trend separated into its own equation for clarity
>
> Method of how χ_v^2 was calculated is not described

Evaluation:

Length:

> Length is appropriate

Title and Abstract Sufficiency:

> Both title and abstract sufficiently describe the research conducted

Contribution to Science:

> Paper provides an additional analysis on the Crab Nebula and a conclusive new view on how to determine its properties and origin

Level of English:

> Paper is easy to read, and language used is understandable

Literary Citations:

All credit is given where due. Introduction and values used are all properly cited

Clarity and Accuracy of Presentation:

Results and process are clearly worked out step by step with all determined properties clearly listed and labeled

Topic Appropriate for Journal:

The topic of this paper is appropriate for this Journal

Data Management Plan:

All data is publicly accessible as well as software used. Process is repeatable

Additional Comments:

This paper is very well constructed. The presentation of necessary background information as well as the process by which the analysis was carried out is clearly described. In the hope that the author accepts these comments, I accept the author's work and compliment them on their hard work and results.

Title: The Crab Nebula's Secret Past: Analysis of the Historical Light Curve of SN 1054 and Implications for the Progenitor

Author: Catherine Petretti

Summary: The author first introduces the Crab Nebula by discussing its origin from the core collapse supernova SN 1054 and the remnant we see today. Although numerous observations of the Crab Nebula exist, astronomers remain unable to determine the core-collapse mechanism or the classification of SN 1054. She presents two models from literature explaining SN 1054: an Fe-core process supernova and an electron capture supernova. The purpose of the author's study is to investigate this uncertainty regarding the classification of the supernova. She collects observations inferred from medieval records for SN 1054 and photometric data from the *Open Supernova Catalog* for various other CCSNe of different types. She compares the light curves to determine the light curve from the supernova catalog that best fits the one inferred for SN 1054. The SN 1054 light curve best matches the light curve for SN 2004dj. This allows the author to approximate the progenitor mass for SN 1054. She finds a much larger progenitor mass than accepted literature which suggests that SN 1054 has more irradiated energy than expected. An analysis of these results suggests that SN 1054 could be a type II-P supernova, but future data analysis would be needed to guarantee this result.

Recommendation: Accept after minor revisions.

Justification of Recommendation:

Major points:

- The data for SN 1054 from medieval records gets compared to data from the *Open Supernova Catalog.* The *Open Supernova Catalog* is, therefore, a major component of the study even though it does not provide the data for the target itself. The author does not explain where the data from this catalog originates or any overview of the catalog itself.
- SN 2008S represents a low-energy ECSN with a type IIn classification. In section 4, the author states that its "low brightness demonstrates why this might not be a suitable framework for SN 1054." It is unclear how the author jumps to this conclusion. An additional sentence or two would help with understanding this method.

Minor points:

- The author assumes error bars of 2 mag and 20 days for the observations from medieval records. She does not explain why she chose these values.
- The author does not specify where she obtained the distance of 2 kpc and the visual extinction of $A_v = 1.6$ mag for SN 1054.
- A single sentence stands alone with tables and graphs on page four. This is a small formatting suggestion, but it would help the reader follow the text of the paper.
- In Section 4, the author does not provide a reference for where she found the velocity for the high neutron star kick of 160 m/s.

Evaluation:

1. Is the length appropriate?
    a. Yes – the length is appropriate, but some parts could use a more in-depth explanation (see justifications above).
2. Are the title and abstract sufficiently informative?
    a. Yes – the title and abstract are both sufficiently informative.
3. Is the contribution to science significant?
    a. Yes – the project investigates uncertainty in the field related to a very famous object. Her results provide new science by fitting supernova light curves to the light curve inferred from historical records.
4. Is the level of English adequate?
    a. Yes – the level of English is adequate.
5. Is the literature properly cited?
    a. Yes – the author sufficiently cites necessary resources.
6. Are the results clearly and accurately presently?
    a. Yes – the results are presented clearly and accurately.
7. Is the topic appropriate for this journal?
    a. Yes – the topic is appropriate for this journal.
8. Data management plan?
    a. The author clearly presents her results and the necessary next steps for confirming the results with results.

Additional Comments: Kudos to the author for investigating such a large question in a short amount of time. She demonstrates a strong understanding of relevant literature and observations, and her results provide an exciting step in understanding SN 1054.

Author: Catherine Petretti

Title: The Crab Nebula's Secret Past: Analysis of the Historical Light Curve of SN 1054 and Implications for the Progenitor

Summary:

The author provides an overview of the Crab Nebula along with its partner, SN 1054 and how they came to be discovered. While providing some properties for SN 1054, the author brings up the issue of how the core-collapse mechanism and the classification of SN 1054 have not yet been determined. The author brings up the current disagreements with the properties of SN 1054 and the classification it would fall under. By constructing a historical light curve along with the light curves of other core collapse supernovae, the author hopes to be able to find the light curve that would best fit SN 1054's records. To do so, x^2_ν was calculated for each light curve and the observations. With the x^2 values at hand for each light curve along with the calculated progenitor mass of 20 solar masses, the author designates SN 2004dj as the one with the closest progenitor mass to SN 1054. As for the classification of SN 1054, the author admits despite the study, no conclusive classification can be given at the moment, but does offer speculation as to why a classification of a type II-P would not be surprising.

Recommendation: Accept with minor revisions.

Justification

Major Points

- The acknowledgement section of the paper should be taken more seriously, assuming the author is thinking of submitting to a journal.
- The author should include a couple sentences of how this study could affect any other work done in astronomy. There seems to be a bubble on the impact this study could potentially have and should be expanded upon.

Minor Points

- The author should provide a time stamp as to when the results from this study will be made public so that further analysis can be conducted.

Evaluation:

1. Appropriate length
    a. Yes, the paper is at the appropriate length.
2. Title and Abstract
    a. While the title is informative, it seems to be a bit excessive. Perhaps the author could try to shorten it. The abstract is also sufficiently informative and explains the study well.
3. Science Contribution
    a. Although the study does provide a contribution to science, there isn't a sense of a greater objective at hand. Outside of the SN from this study, the author should mention how this can impact the field in general.
4. Level of English
    a. Yes, the English level is adequate.
5. Literature
    a. Yes, the literature presented is cited properly.
6. Results
    a. Dwd
7. Topic
    a. Yes, the topic is appropriate for this journal.
8. Data Management Plan
    a. Though the author encourages further analysis to confirm the results, it is not specifically mentioned when/how the data will become available.

Additional Comments: The paper reads well and tackles all of the objectives the author set forth. Well done.

Summary

Even though the Crab Nebula is one of the most famous supernovae, scientists have had trouble classifying it up to date. There are two opposing models to try to classify it, an iron-core collapse and an electron capture supernova. However, this author believes that an electron capture supernova would not yield enough energy to explain the Crab Pulsar's speed. What this author aims to do is use the first ever observations of this supernova to make a light curve, calculate the mass of the progenitor, and to try and suggest that it is a core collapse supernova by comparing it with other light curves. The author used medieval records to infer and then plot the historical light curve. She used the Open Supernova Catalogue to obtain many other light curves based on certain criteria which she overlaid on the historical data. She then figured out which of the supernovae seemed to best fit the historical data points, and inferred the mass of the Crab progenitor. Because a certain light curve fits the historical points best, the masses may be similar. In the Discussion, the author compares the results to the literature and comes to the conclusion that SN1054 was likely an iron core collapse supernova. She suggests it could be a supernova Type II-P, but this classification is still quite uncertain and requires more analysis that can be done in the future.

Recommendation

Accept with minor revision.

Justification of Recommendation

Major points:

1. There were no issues that compromised the integrity of the paper.

Minor points:

1. There is one sentence in the abstract: "Using this trend, I estimate the progenitor mass of SN 1054 from the irradiated power of SN 2004dj to be 20 Msun while the progenitor mass is well established to be ~ 8−10 Msun." I was initially confused by the wording and I think it could be rephrased so that the reader understands better.
2. There are a few grammatical errors which should be fixed with some more proofreading.
3. In the last sentence in the abstract, maybe it would be beneficial for the author to explain why the statement is the case. It is kind of just left wide open and as the reader I do wish there were a few more words of explanation.
4. The author refers to a neutron star kick twice in the paper. I know that this is meant for experts in the field, but I do not know what that means.
5. At the end of the introduction, I would have liked to see a brief outline of the paper describing what is to be talked about in each section.
6. In the beginning of Observations, the author states that "observations were inferred…." Who were they inferred by? The author of this paper or Nomoto et al 2014?
7. In the description for Equation 1, the author mentions a different equation with the variable *z*, but I am not sure what *z* means.
8. In the methodology, it would be good to state the chi squared equation used and what this value actually signifies.

9. In the paragraph before the discussion, the author states that the progenitor masses were obtained from literature, but I would like to know the literature they came from in the text of the paper. I see they are also listed in Table 1. Another option is to say that the masses plus the references are available in Table 1.
10. The author says that the classification for the supernova “might not be surprising.” It would be better to reword this so that it sounds more professional.

Evaluation

1. Paper length
    a. The length is very appropriate. It does not need any more information but at the same time it is very concise.
2. Title & abstract
    a. The title definitely reflects the summary and the abstract also properly reflects the goals and outcome of this project.
3. Contribution to science
    a. The project does significantly contribute to science. It helps contribute to the solution for a big misunderstanding within the supernova field.
4. Level of English
    a. The level of English is very adequate. I understand mostly everything the author is trying to say throughout the entire paper.
5. Literature
    a. There is a very strong backing of literature and there was not a single claim left open ended or unexplained, besides one in the observations. The author says “medieval records,” but I am not sure what those are.
6. Presentation of results
    a. The results from the project are not really cited in a Table, but I think they are supposed to be more descriptive than numerical. The masses and classifications used from literature though are clearly presented and any graphs have errors.
7. Topic appropriateness
    a. The topic is appropriate for the journal.

Data Management

The results are definitely reusable. Future authors can likely take these results and use them to research their own results, as this author did with those from the past.

Additional Comments

Congratulations to the author for completing this report in such a short period of time. I hope her future endeavors will treat her well.