Peer Review File

Manuscript Title: Minutes-duration Optical Flares with Supernova Luminosities

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

I have reviewed "Minute-timescale Optical Flares with Supernova Luminosities, Months After an Extragalactic Transient" by Ho et al. The authors present the discovery of minute-duration very high amplitude non-thermal optical flares emerging out of the fading continuum of (what they argue to be) a member of the nascent class of engine-powered luminous fast blue optical transients (LFBOT).

This review will be short because I feel the case for publication is strong.

The authors make a compelling case for their interpretation of this event as a member of the LFBOT class, in terms of extremely luminous and fast-fading optical light curve, early-featureless optical spectrum, host galaxy association (firming of an extragalactic origin), the now-hallmark bright radio/mm emission from CSM interaction, and highly luminous long-lasting variable X-ray emission.

As the authors note, the discovery of such short highly luminous flares at such late times, from an optically-selected supernova-like transient, is unprecedented. It also has important ramifications for the origins of LFBOTs more broadly, by quelching any remaining doubt that these events are powered by long-lived active central engine (accreting black holes or rapidly spinning magnetars), a fact which might still have beeen reasonably questioned before this discovery. The discovery alone merits publication in Nature.

The discovery is also remarkable insofar that it shows that we can receive extremely short timescale flares from either a ~months-old magnetar or a highly-super Eddington accreting black hole, that likely track directly down to the activity of the central engine. As the authors note, late flares are seen at late times in some GRB, but tracing them directly to ongoing outflows of the central engine is less trivial than in this case.

The authors also make a reasonable and even-handed agnostic case from the brightness temperature, variability time, and requirement that the outflow be optically-thin, that the emission is non-thermal and the emitting region needs to be expanding at least mildly relativistic towards the observer (though I have some questions on their analysis in my detailed comments below).

In short, I find this discovery remarkable and find relatively little to quibble with regarding on presented analysis. With some minor tweaks, I would be able to endorse publication of the article in Nature.

COMMENTS/SUGGESTIONS

Main text.

** "Force photometry...at the position of the transient revealed additional flares, the first at \Delta t_rest = 21 d". It may be worth clarifying that this time interval is from the first flare detection, not the first detection of the transient.

** "Previousy observed flare behavior is... at much higher energies (e.g., magnetar giant flares)". Maybe worth clarifying to "much higher *photon* energies".

** "If AT2022tsd arose from a stellar-mass black hole, the accretion rate would be highly super-Eddington (1e5 L_edd for a 10 Msun black hole without relativistic beaming)", perhaps amend to "without relativistic *or* geometric beaming". Some of the high-luminosities of ULX, for instance, have been attributed to geometric beaming by the accretion funnel that may not require outwards relativistic motion of the emitting region. Though I realize that the statistics of LFBOTs suggest that a highly pole-on viewing angle is unlikely, which probably limits any pure geometric beaming to a factor of 10 or less.

Methods.

** In Section 7 of the methods, the authors argue (somewhat off hand) against a Gamma ~ 100 outflow based on the lack of a GRB detection. However, I find this unconvincing because the total luminosity/energy of the individual flares is also much lower than in a GRB. I would recommend being more agnostic about the Lorentz factor of the outflow.

** Related: I am not sure how to reconcile the E_rad ~ 1e46-1e47 erg in radiated isotropic energy, with the equipartition argument finding an energy U_eq ~ 1e43 (Gamma^2.6) unless either (1) the flare was highly radiatively efficient (E_rad >> U_eq); (2) the outflow was in fact ultra-relativistic with Gamma >~ 100. However, possibility (1) of highly radiatively efficient emission seems inconsistent with the observed spectral slope being that of optically-thin synchrotron emission from *slow-cooling* electrons. The authors should address how to reconcile these two issues without the outflow being ultra-relativistic.

** With regards to the L_X ~ t^-2 decay, Metzger 2022 point out this is consistent also what one predicts for the accretion rate onto the central object from a viscously spreading super-Eddington (radiatively inefficient) disk of a fixed initial mass (e.g. that produced by a tidal disruption of a star), where one predicts Mdot ~ -4*(p+1)/3, where Mdot ~ r^p accounts for mass-loss from the super-Eddington disk for values p ~ 0.5 close to what is found by numerical simulations of radiatively inefficient accretion flows (as summarized e.g. in Yuan & Narayan 2014).

Referee #2 (Remarks to the Author):

In the manuscript "Minute-timescale Optical Flares with Supernova Luminosities, Months After an Extragalactic Transient", Ho et al. report the unanticipated discovery of short timescale variability in the late-time light curve of the luminous fast blue optical transient (LFBOT) AT2022tsd. The discovery is quite remarkable, and may be will one of the key clues to the origin(s) of this new class of astrophysical transients. The manuscript is generally well written, and the source is supported with extensive observational data (rare for an LFBOT). I also expect the result to be of general interest to the non-astronomer Nature reader. But I do have a number of issues I'd like to see addressed before recommending publication.

More significant concerns:

- The manuscript presents extensive radio (cm and mm wavelength) observations of the source, with nice plots showing comparisons with known LFBOTs and transients from other classes (e.g., Figure 2, Extended Data Figure 3). But to the best of my knowledge there is no real analysis of these radio observations - e.g., equipartition analysis to estimate the size of the radio emitting region, the velocity of the fastest moving ejecta, etc. This seems like a significant omission - the flares are argued to come from a "jet", and a good deal of effort goes into estimating the radius where the optical flares are coming from. Analysis of the radio emission should be included here (and not, e.g., in a separate manuscript), or if for some reason such an analysis cannot be performed, the reasons for this should be explicitly stated.

- Regarding the physical origin of the AT2022tsd's flares (e.g., Methods Section 7 and throughout), I think it is quite important to estimate the properties (spectrum, radius, etc.) of the *non-flaring* emission, in particular at UV/optical wavelengths. If I take AT2018cow as an analog, the UV/optical SED is reasonably well-described by a blackbody (modulo the reddest NIR bands), and the derived effective radius is > 10^14 cm. Presumably something similar holds for AT2022tsd (the authors can at least provides a consistency check). Given the emitting size derived from for the flares (> 10^12 * Gamma^2), this could have important implications. Either the material responsible for the flares needs to be expanding with a very large Lorentz factor at this time (>~ 10), or the non-thermal flare emission needs to someone find its way through an extended optically thick envelope unaffected.

Combining both of the notes above, I think a summary of the basic constraints (radius, optical depth, etc.) derived for the multiple emission components is critical to our understanding of this source. I don't believe the authors necessarily need to resolve any potential contradictions within these results, but at least these should be put out there for the community to digest.

- The final paragraph suggests that these sources may be discovered in current and future wide-field optical surveys with high cadences. Setting aside the issue of finding objects in single images, without some rate estimate there is no way to determine if these surveys are actually capable of making such discoveries. I suggest either estimate the observable rate of such events, or dropping the discussion of future discoveries of such phenomena.

Other more minor suggestions:

- Line 123: GRB080319B should be GRB070610

- In the top panel of Figure 3, it is very hard to visually ascertain the brightness of AT2022tsd, with such few/faint reference stars for comparison shown in the cutouts.

- In Methods Section 5, it is worth pointing out that the quoted limits are for sources with typical GRB prompt emission time scales. Something with a much longer time scale (e.g., the ultra-long "GRB" that turned in Swift J1644) would be appreciably different.

- In Methods Section 7, I find it confusing to have Equations 2 and 3 in mks units, but everything else in cgs units (and the units in Equation 2 seem wrong to me to begin with, though I'm not all that used to working in mks).

We would like to thank the editor and the referees for providing comments on our manuscript "Minutes-duration Optical Flares with Supernova Luminosities." The suggestions and feedback have greatly improved the paper. Below we provide point-by-point responses to the referee reports and to the editorial suggestions.

Referee 1: Theory

Main text.

*** "Force photometry...at the position of the transient revealed additional flares, the first at \Delta t_rest = 21 d". It may be worth clarifying that this time interval is from the first flare detection, not the first detection of the transient.*

We thank the referee for pointing out that the language in this section was unclear. We have amended the text to clarify that this time interval is from the first detection of the transient (line 64).

*** "Previousy observed flare behavior is... at much higher energies (e.g., magnetar giant flares)". Maybe worth clarifying to "much higher *photon* energies".*

We have incorporated the referee's suggestion (line 90).

*** "If AT2022tsd arose from a stellar-mass black hole, the accretion rate would be highly super-Eddington (1e5 L_edd for a 10 Msun black hole without relativistic beaming)", perhaps amend to "without relativistic *or* geometric beaming". Some of the high-luminosities of ULX, for instance, have been attributed to geometric beaming by the accretion funnel that may not require outwards relativistic motion of the emitting region. Though I realize that the statistics of LFBOTs suggest that a highly pole-on viewing angle is unlikely, which probably limits any pure geometric beaming to a factor of 10 or less.*

We have made this change (line 128).

Methods.

*** In Section 7 of the methods, the authors argue (somewhat off hand) against a Gamma ~ 100 outflow based on the lack of a GRB detection. However, I find this unconvincing because the total luminosity/energy of the individual flares is also much lower than in a GRB. I would recommend being more agnostic about the Lorentz factor of the outflow.*

We thank the referee for raising this point. We agree and have removed the suggestion that Gamma ~ 100 is unlikely for this object (line 712).

*** Related: I am not sure how to reconcile the E_rad ~ 1e46-1e47 erg in radiated isotropic energy, with the equipartition argument finding an energy U_eq ~ 1e43 (Gamma^2.6) unless* *either (1) the flare was highly radiatively efficient (E_rad >> U_eq); (2) the outflow was in fact ultra-relativistic with Gamma >~ 100. However, possibility (1) of highly radiatively efficient emission seems inconsistent with the observed spectral slope being that of optically-thin synchrotron emission from *slow-cooling* electrons. The authors should address how to reconcile these two issues without the outflow being ultra-relativistic.*

The referee makes a very good point. We have added text to this section discussing the two possible explanations raised (line 740).

*** With regards to the L_X ~ t^-2 decay, Metzger 2022 point out this is consistent also what one predicts for the accretion rate onto the central object from a viscously spreading super-Eddington (radiatively inefficient) disk of a fixed initial mass (e.g. that produced by a tidal disruption of a star), where one predicts Mdot ~ -4*(p+1)/3, where Mdot ~ r^p accounts for mass-loss from the super-Eddington disk for values p ~ 0.5 close to what is found by numerical simulations of radiatively inefficient accretion flows (as summarized e.g. in Yuan & Narayan 2014).*

We added this reference to the discussion about the L_X ~ t^{-2} decay (line 490).

Referee 2: Observations

- *The manuscript presents extensive radio (cm and mm wavelength) observations of the source, with nice plots showing comparisons with known LFBOTs and transients from other classes (e.g., Figure 2, Extended Data Figure 3). But to the best of my knowledge there is no real analysis of these radio observations - e.g., equipartition analysis to estimate the size of the radio emitting region, the velocity of the fastest moving ejecta, etc. This seems like a significant omission - the flares are argued to come from a "jet", and a good deal of effort goes into estimating the radius where the optical flares are coming from. Analysis of the radio emission should be included here (and not, e.g., in a separate manuscript), or if for some reason such an analysis cannot be performed, the reasons for this should be explicitly stated.*

We agree with the referee that this analysis should be included in the paper. We have added it in a new Methods section 9.

- *Regarding the physical origin of the AT2022tsd's flares (e.g., Methods Section 7 and throughout), I think it is quite important to estimate the properties (spectrum, radius, etc.) of the *non-flaring* emission, in particular at UV/optical wavelengths. If I take AT2018cow as an analog, the UV/optical SED is reasonably well-described by a blackbody (modulo the reddest NIR bands), and the derived effective radius is > 10^14 cm. Presumably something similar holds for AT2022tsd (the authors can at least provides a consistency check). Given the emitting size derived from for the flares (> 10^12 * Gamma^2), this could have important implications. Either the material responsible for the flares needs to be expanding with a very large Lorentz factor at this time (>~ 10), or the non-thermal flare emission needs to someone find its way through an extended optically thick envelope unaffected.*

We agree with the referee that this analysis should be included in the paper. We have added it in a new Methods section 8 and discussed ways to reconcile the inferred radii.

- *Combining both of the notes above, I think a summary of the basic constraints (radius, optical depth, etc.) derived for the multiple emission components is critical to our understanding of this source. I don't believe the authors necessarily need to resolve any potential contradictions within these results, but at least these should be put out there for the community to digest.*

We thank the referee for the excellent suggestion. We have created a summary of the basic constraints (Table 1).

- *The final paragraph suggests that these sources may be discovered in current and future wide-field optical surveys with high cadences. Setting aside the issue of finding objects in single images, without some rate estimate there is no way to determine if these surveys are actually capable of making such discoveries. I suggest either estimate the* *observable rate of such events, or dropping the discussion of future discoveries of such phenomena.*

We deleted the final paragraph.

- *Line 123: GRB080319B should be GRB070610*

This sentence has been removed as part of our need to shorten the main text.

- *In the top panel of Figure 3, it is very hard to visually ascertain the brightness of AT2022tsd, with such few/faint reference stars for comparison shown in the cutouts.*

We updated the figure, zooming out to show more reference objects for comparison.

- *In Methods Section 5, it is worth pointing out that the quoted limits are for sources with typical GRB prompt emission time scales. Something with a much longer time scale (e.g., the ultra-long "GRB" that turned in Swift J1644) would be appreciably different.*

We have added this point to Methods section 5 (lines 671-2).

- *In Methods Section 7, I find it confusing to have Equations 2 and 3 in mks units, but everything else in cgs units (and the units in Equation 2 seem wrong to me to begin with, though I'm not all that used to working in mks).*

We rewrote Equations 2 and 3 in cgs units.

Reviewer Reports on the First Revision:

Referee #2 (Remarks to the Author):

I thank the authors for addressing all of my previous comments. I'm happy to recommend the manuscript for publication now. Congratulations on the very interesting discovery!