Minutes-duration Optical Flares with Supernova Luminosities

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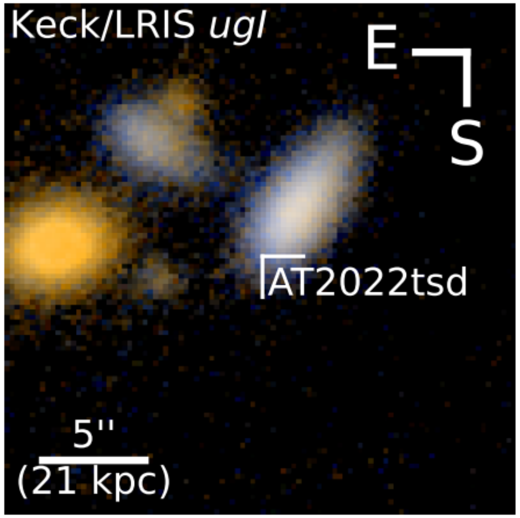
Introduction

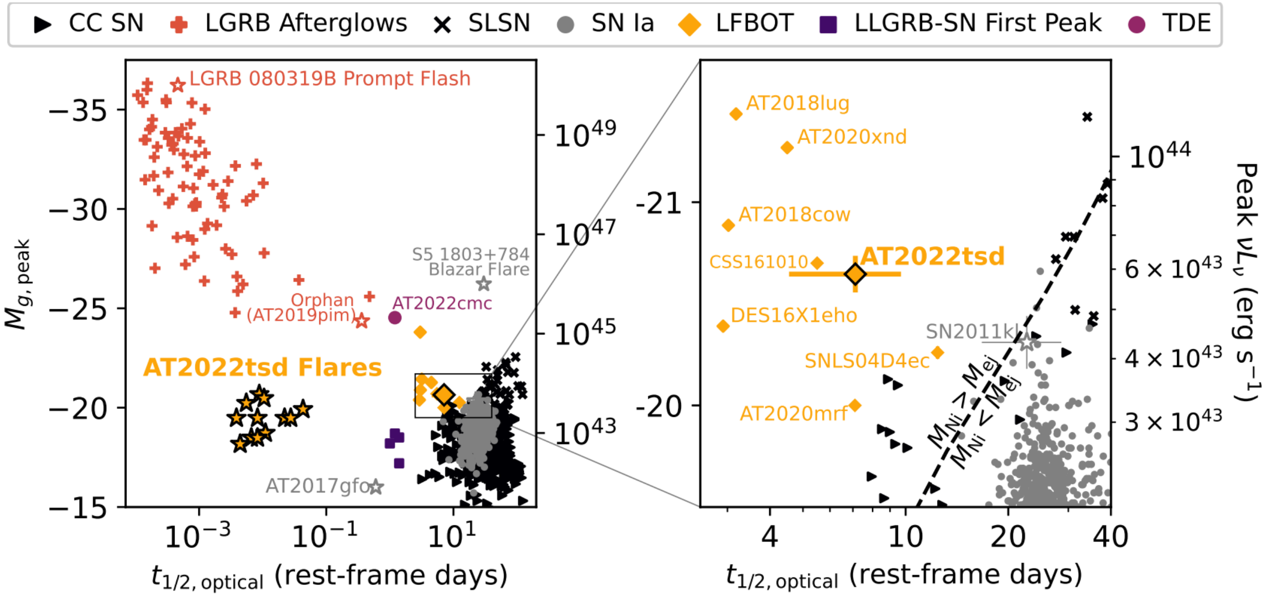
- The development of wide-field, high cadence and deep optical surveys in recent years, including ZTF, ATLAS, PanSTARRS, is leading to ever more transient detections in the extremes of parameter space.
- Such surveys led to the discovery of fast blue optical transients (FBOTs), first identified as a class by Drout et al. (2014) in ZTF. FBOTs rise and fade on timescales of days, have (early-time) g-r colours of -0.3 or bluer, have featureless, black-body-like spectra at early time with inferred temperatures > 10^4 K (Pursiainen et al. 2018)
- It has since become clear that the majority are infant supernovae with low ejecta masses.
- A small number fade too rapidly to be powered by Ni-56 decay (faster than 0.2-0.3 magnitudes per day), have peak absolute magnitudes rivalling superluminous supernovae (< -20), and have accompanying luminous X-ray and radio emission —— dubbed as ‘luminous-FBOTs’ (LFBOTs, Metzger 2022), whose origins are poorly understood.
- The prototypical example is AT2018cow.
- Since AT2018cow, several other LFBOTs have been discovered, including ZTF18abvkwla ("the Koala", Ho et al. 2020), CSS161010 (Coppejans et al. 2020), ZTF20acigmel ("the Camel", Perley et al. 2021), and AT2020mrf (Yao et al. 2022).
- Despite the growing number of LFBOT discoveries, these events are intrinsically rare - the volumetric rate of AT2018cow-like LFBOTs is estimated to be no more than 0.1 percent of the local supernova rate (Ho et al. 2023).

AT2022tsd - a luminous and fast-evolving optical transient

- The Zwicky Transient Facility detected a new optical transient AT2022tsd (α = 03h20m10s.873, δ = +08◦44′55″.739, 30s exposures, r = 20.36 ± 0.23 mag) as part of its public two-day cadence all-sky survey at 11:21:22 on 2022 September 7 (UTC).
- Forced photometry on ZTF images revealed that the light-curve evolution was faster than that of typical supernovae.

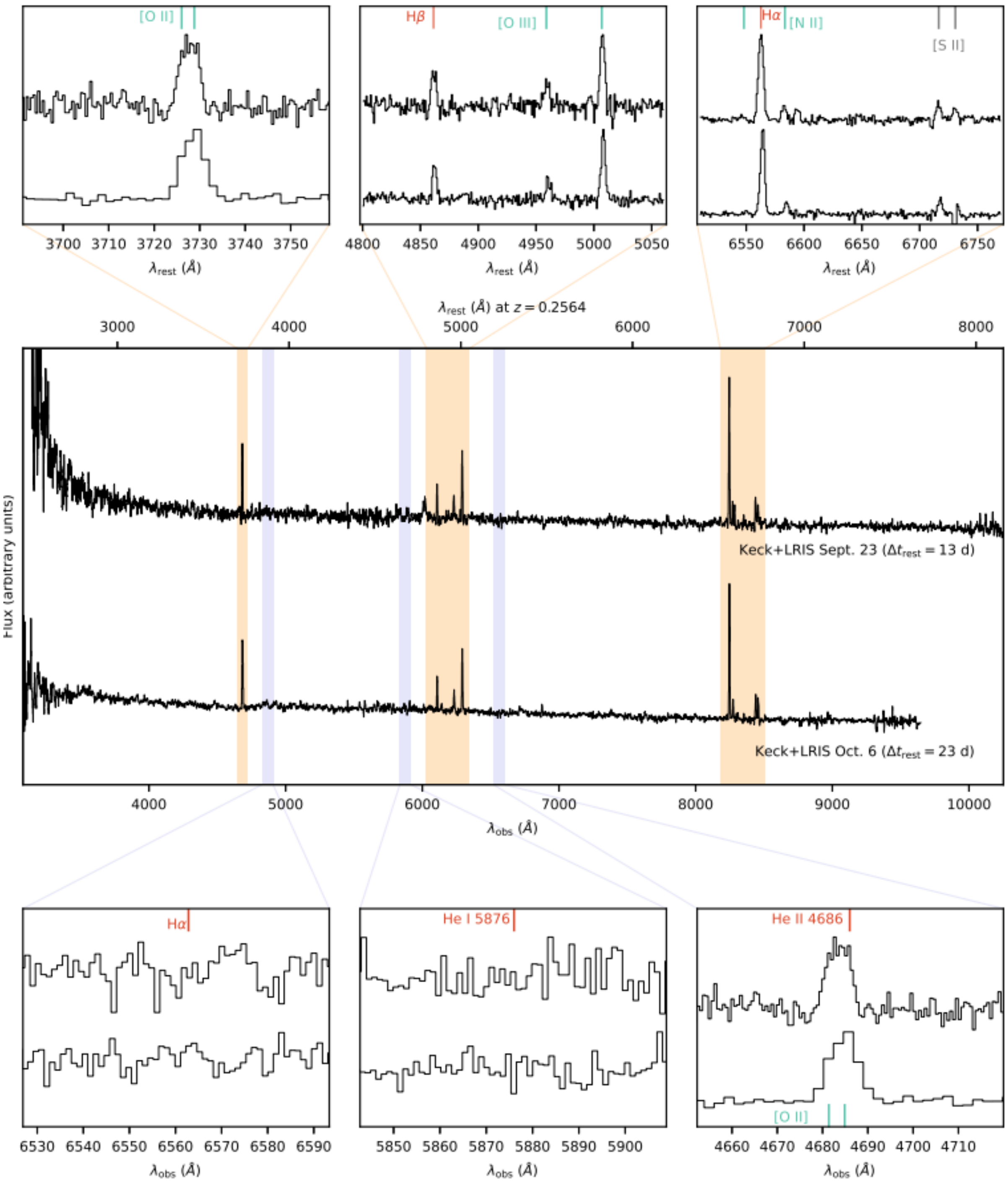


Keck/LRIS false-colour u/g/I image



Duration above half-maximum light vs. peak absolute magnitude

Optical spectra obtained with Keck/LRIS



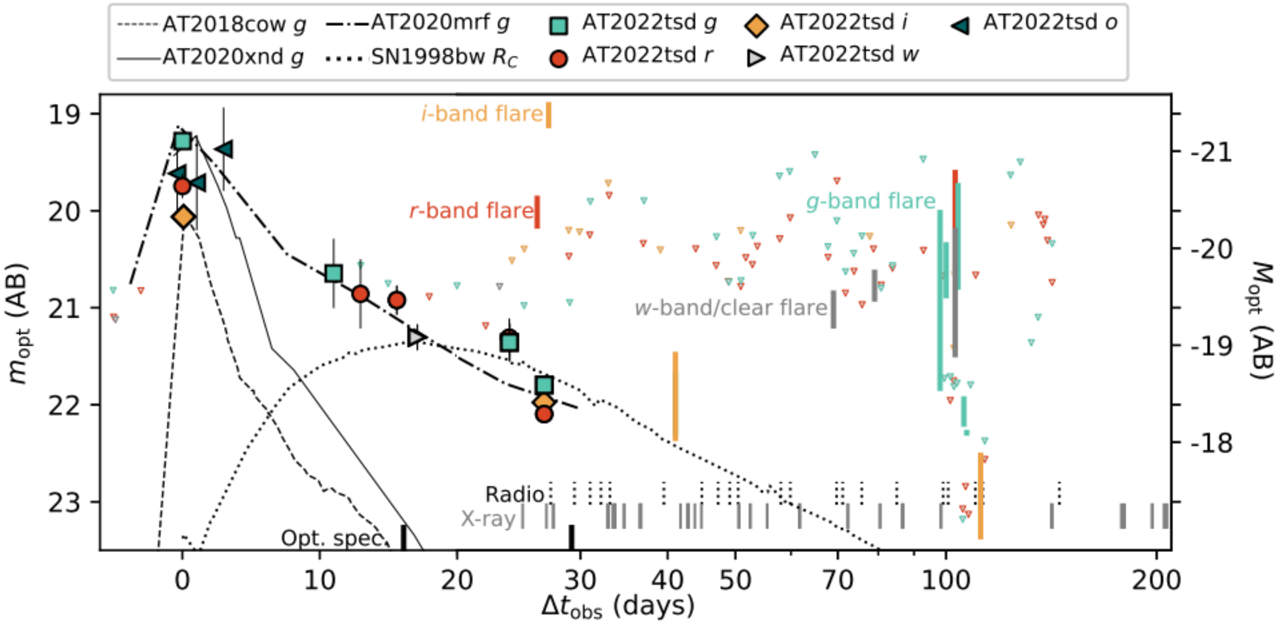
Two spectra of AT2022tsd with the Low Resolution Imaging Spectrometer (LRIS) on the Keck I 10-m telescope were obtained on Sept. 23 and Oct. 6.

Regions with identified narrow host-galaxy emission lines, give rise to the best-fit redshift of $z = 0.2564 \pm 0.0003$

Light curves of AT2022tsd

The multiwavelength properties of AT2022tsd are most similar to those of AT2018cow-like transients (also referred to as luminous fast blue optical transients or “LFBOTs”), suggesting a common origin.

- Fast light-curve evolution
- The implied high peak luminosity
- The lack of prominent spectroscopic features after the transient faded by 2–3 magnitudes



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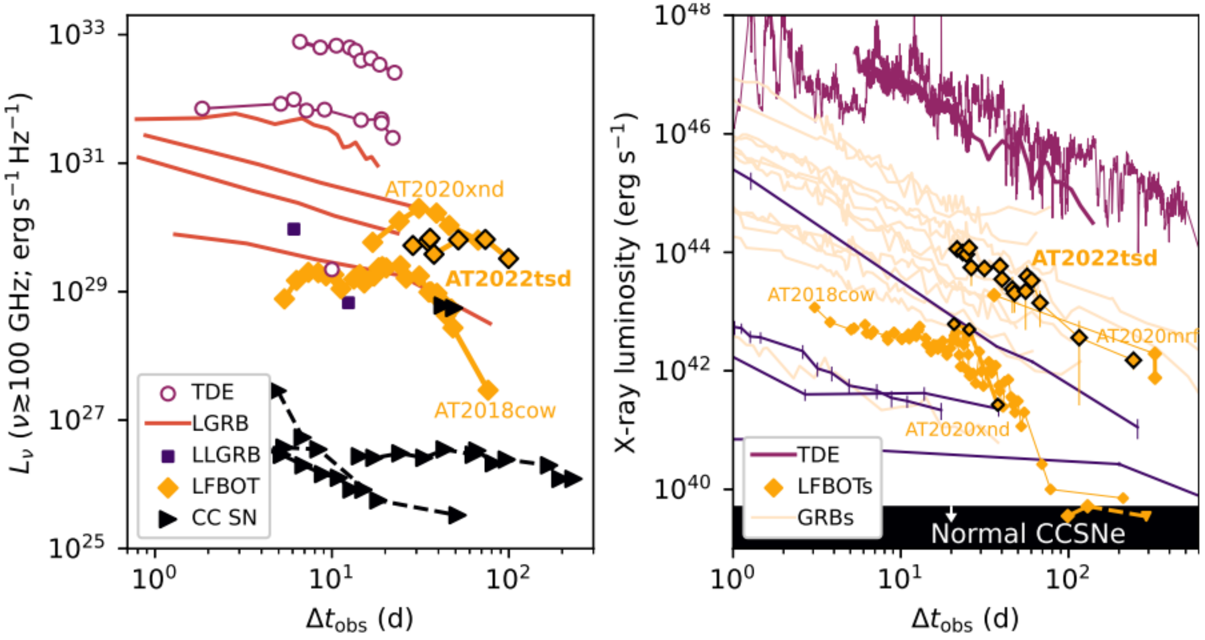
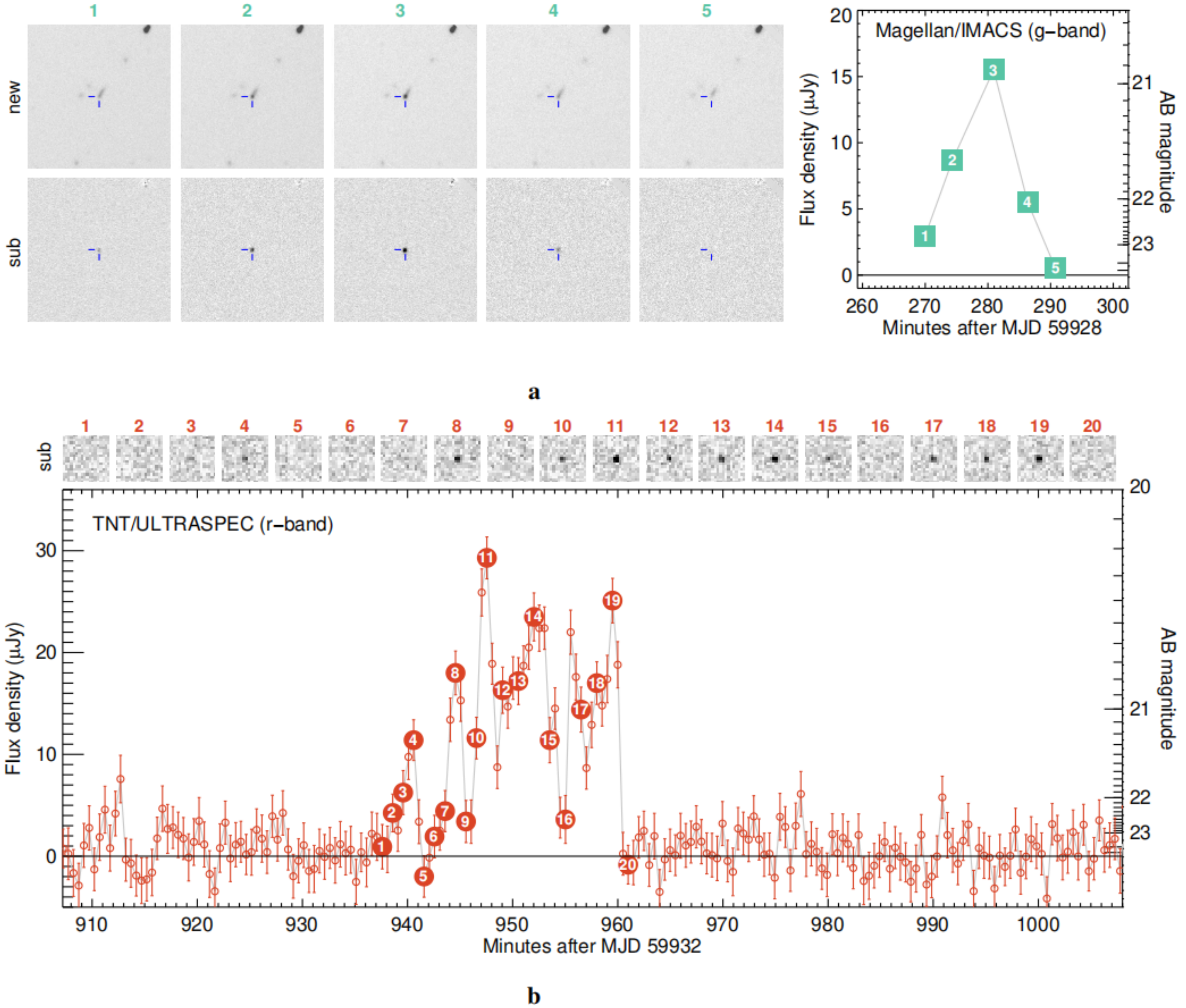


AT2022tsd exhibited luminous flares lasting tens of minutes on 2022 December 15 and December 19

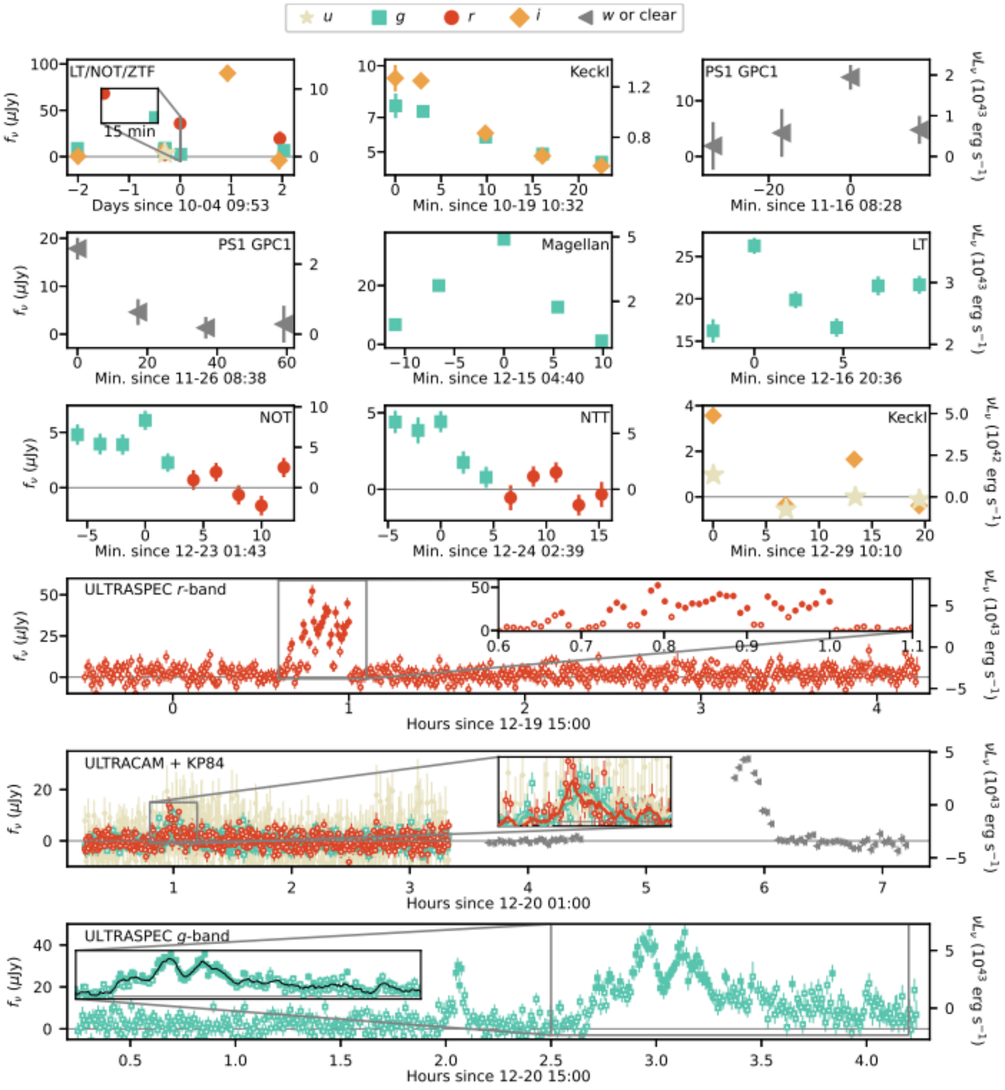


More luminous flares

Forced photometry on ZTF and Pan-STARRS survey images at the position of the transient revealed previous flare detections, as early as 26 d (observer frame) after the initial transient discovery

They obtained a total of 60 hr of optical observations of AT2022tsd on 20 different nights, using 13 different telescopes. The duration of each sequence ranged from 10 min to 4.5 hr. In total they detected at least 14 flares

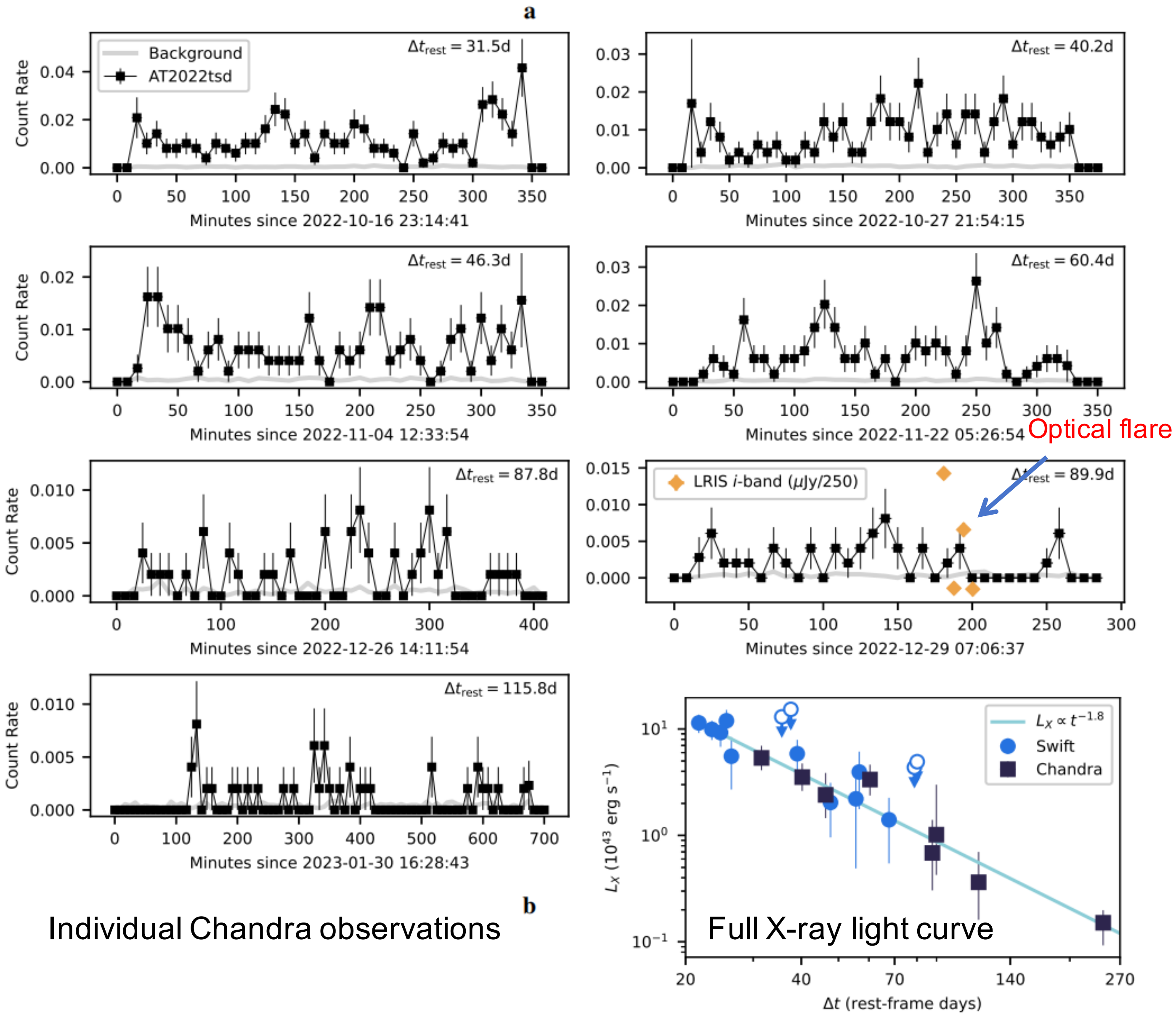
Complex temporal profiles were found to vary between flares



X-ray variability, but no X-ray flare counterpart

X-ray observations revealed X-ray variability on timescales of tens of minutes, but no clear high-amplitude flares.

They detected one definitive optical flare during X-ray monitoring, but no X-ray flare counterpart was detected



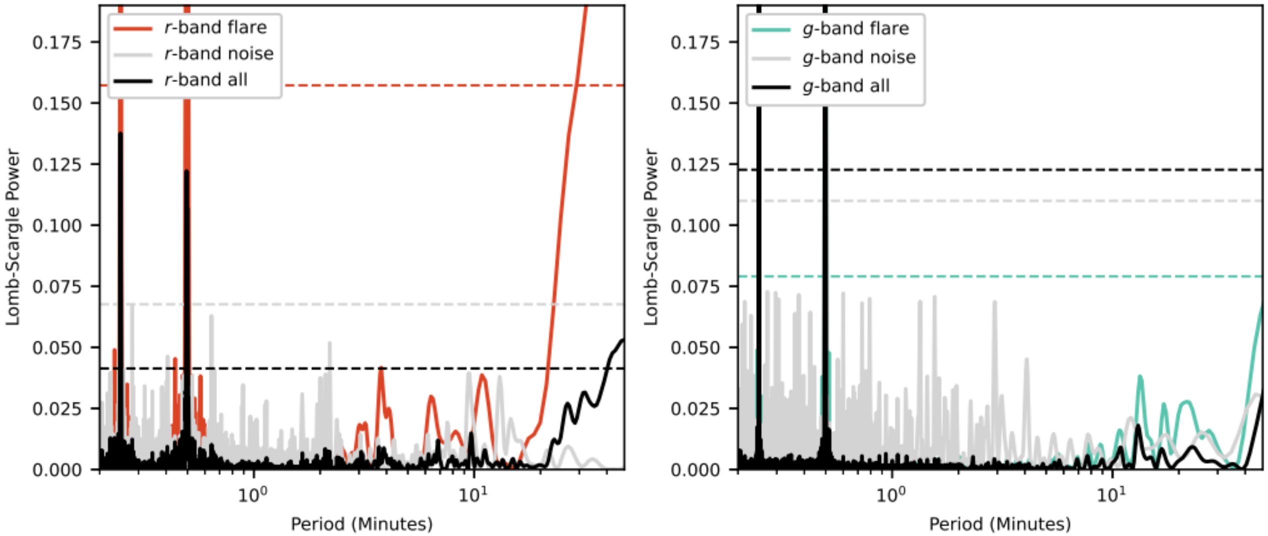
Optical flare

Individual Chandra observations

Full X-ray light curve

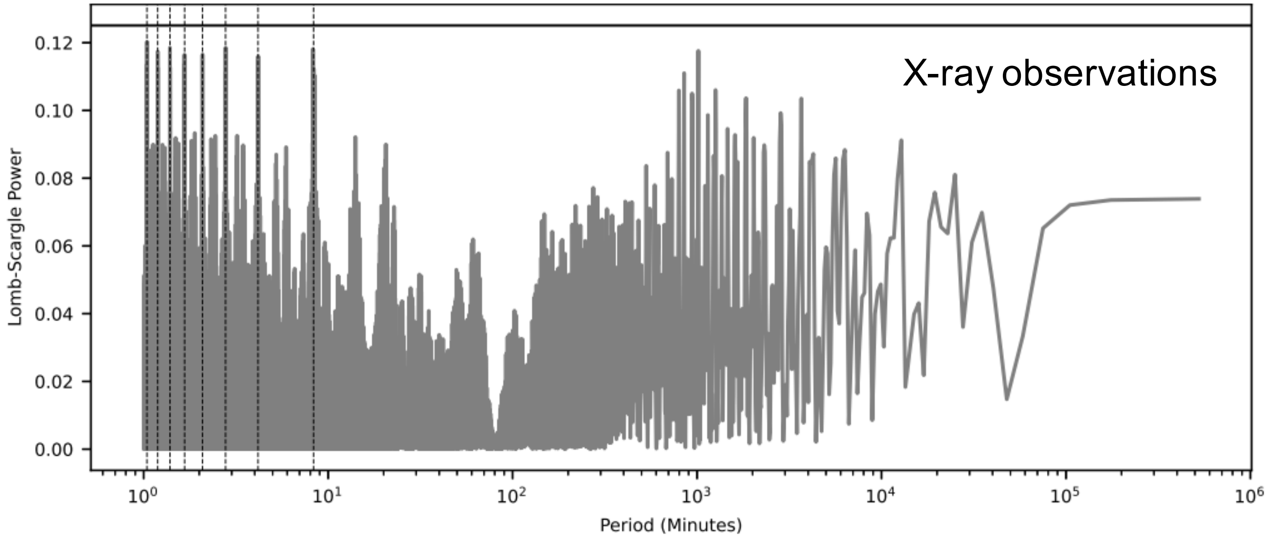
No clear periodicity between or within flares in either the optical or X-ray emission

The only peaks higher than this threshold are from the cadence of the observation (30 s, and an alias at half that value), from the overall flare width, and from the duration of the observation.

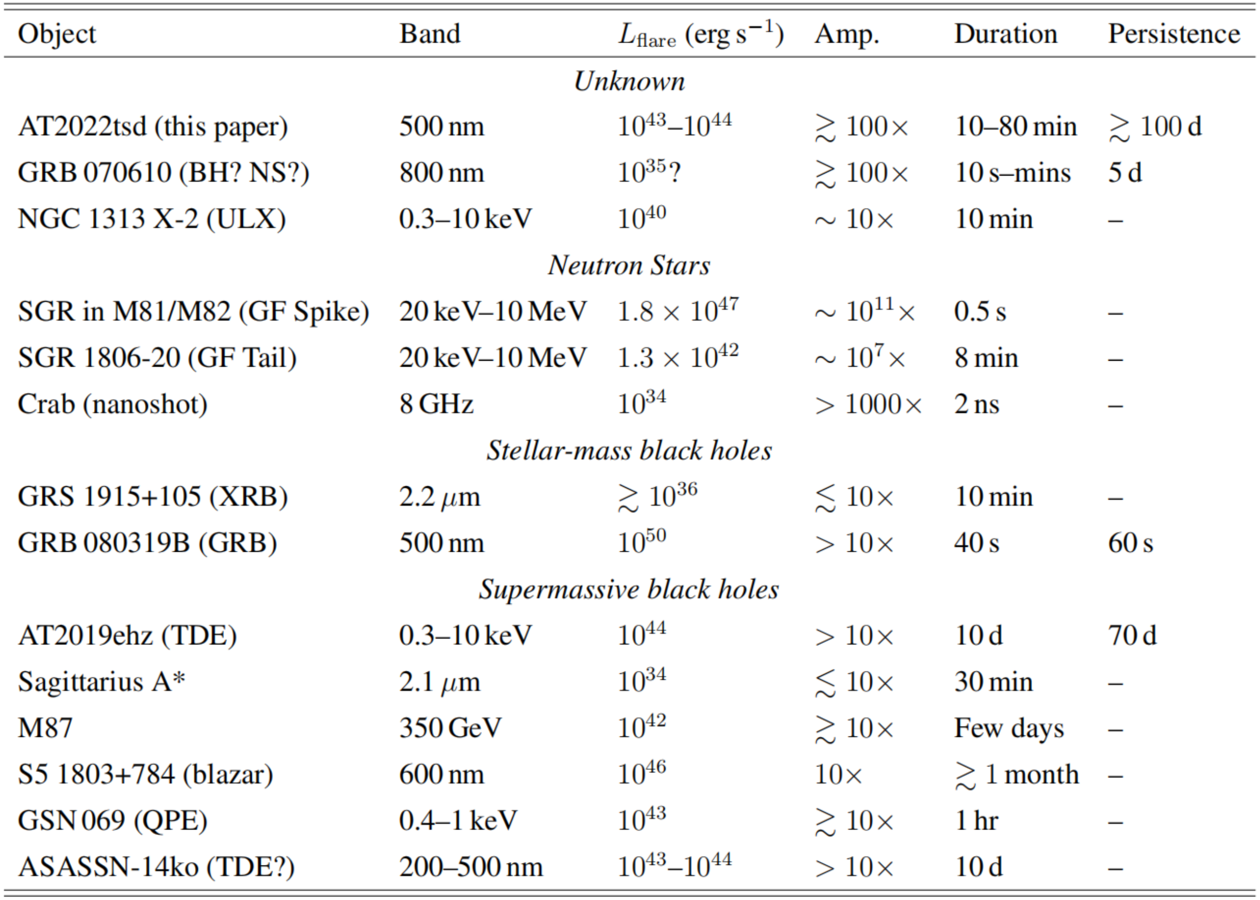


Lomb-Scargle periodogram of the ULTRASPEC optical flares
Horizontal dashed lines mark the power expected for a false-alarm peak

The observed peaks arise from the 500s sampling and aliases (marked with vertical dotted lines).



This phenomenon — minute-timescale optical flares at supernova-like luminosities, with order-of-magnitude amplitude variations, persisting for 100 days — has no precedent in the literature.

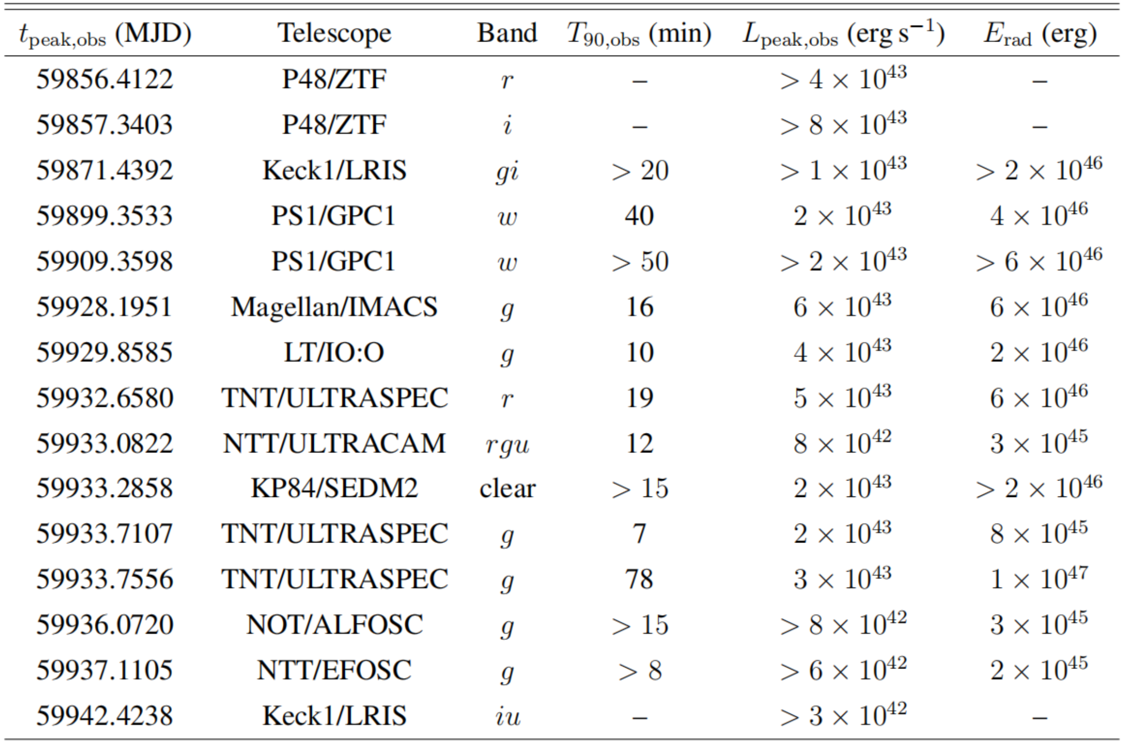


Object	Band	$L_{\rm flare}$ (erg s^{-1})	Amp.	Duration	Persistence
		Unknown			
AT2022tsd (this paper)	500 nm	10^{43}–10^{44}	$\gtrsim 100\times$	10–80 min	$\gtrsim 100$ d
GRB 070610 (BH? NS?)	800 nm	10^{35}?	$\gtrsim 100\times$	10 s–mins	5 d
NGC 1313 X-2 (ULX)	0.3–10 keV	10^{40}	$\sim 10\times$	10 min	–
		Neutron Stars			
SGR in M81/M82 (GF Spike)	20 keV–10 MeV	1.8×10^{47}	$\sim 10^{11}\times$	0.5 s	–
SGR 1806-20 (GF Tail)	20 keV–10 MeV	1.3×10^{42}	$\sim 10^{7}\times$	8 min	–
Crab (nanoshot)	8 GHz	10^{34}	$> 1000\times$	2 ns	–
		Stellar-mass black holes			
GRS 1915+105 (XRB)	2.2 μm	$\gtrsim 10^{36}$	$\lesssim 10\times$	10 min	–
GRB 080319B (GRB)	500 nm	10^{50}	$> 10\times$	40 s	60 s
		Supermassive black holes			
AT2019ehz (TDE)	0.3–10 keV	10^{44}	$> 10\times$	10 d	70 d
Sagittarius A*	2.1 μm	10^{34}	$\lesssim 10\times$	30 min	–
M87	350 GeV	10^{42}	$\gtrsim 10\times$	Few days	–
S5 1803+784 (blazar)	600 nm	10^{46}	$10\times$	$\gtrsim$ 1 month	–
GSN 069 (QPE)	0.4–1 keV	10^{43}	$\gtrsim 10\times$	1 hr	–
ASASSN-14ko (TDE?)	200–500 nm	10^{43}–10^{44}	$> 10\times$	10 d	–

- Previously observed flaring behaviour was either orders of magnitude less luminous, persisted for only a few minutes, had much longer durations, or was at much higher photon energies.
- The fact that these optical flares were observed in the aftermath of an extragalactic transient is even more unusual.

Physical properties of the flares in AT2022tsd

- The fast variability timescale of the flares implies an emitting-region radius $< (9 \times 10^{11}\ \mathrm{cm})\Gamma^2$
- A brightness temperature of $T_B > (2 \times 10^{10}\ \mathrm{K})\Gamma^{-4}$
- The high brightness temperature, combined with the red flare colour, implies a nonthermal emission mechanism such as optically thin synchrotron radiation.
- The flares are extremely energetic, with 10^{46}–10^{47} erg in radiated energy alone per detected flare.
- The timescales, the enormous energetics, the high brightness temperature, and the requirement of optically thin emission for the flares strongly implies that the flare-emitting outflow has at least near-relativistic ($v/c \gtrsim 0.6$) velocities



$t_{\mathrm{peak,obs}}$ (MJD)	Telescope	Band	$T_{90,\mathrm{obs}}$ (min)	$L_{\mathrm{peak,obs}}$ (erg s^{-1})	E_{rad} (erg)
59856.4122	P48/ZTF	r	–	$> 4 \times 10^{43}$	–
59857.3403	P48/ZTF	i	–	$> 8 \times 10^{43}$	–
59871.4392	Keck1/LRIS	gi	> 20	$> 1 \times 10^{43}$	$> 2 \times 10^{46}$
59899.3533	PS1/GPC1	w	40	2×10^{43}	4×10^{46}
59909.3598	PS1/GPC1	w	> 50	$> 2 \times 10^{43}$	$> 6 \times 10^{46}$
59928.1951	Magellan/IMACS	g	16	6×10^{43}	6×10^{46}
59929.8585	LT/IO:O	g	10	4×10^{43}	2×10^{46}
59932.6580	TNT/ULTRASPEC	r	19	5×10^{43}	6×10^{46}
59933.0822	NTT/ULTRACAM	rgu	12	8×10^{42}	3×10^{45}
59933.2858	KP84/SEDM2	clear	> 15	2×10^{43}	$> 2 \times 10^{46}$
59933.7107	TNT/ULTRASPEC	g	7	2×10^{43}	8×10^{45}
59933.7556	TNT/ULTRASPEC	g	78	3×10^{43}	1×10^{47}
59936.0720	NOT/ALFOSC	g	> 15	$> 8 \times 10^{42}$	3×10^{45}
59937.1105	NTT/EFOSC	g	> 8	$> 6 \times 10^{42}$	2×10^{45}
59942.4238	Keck1/LRIS	iu	–	$> 3 \times 10^{42}$	–

Physical properties of AT2022tsd

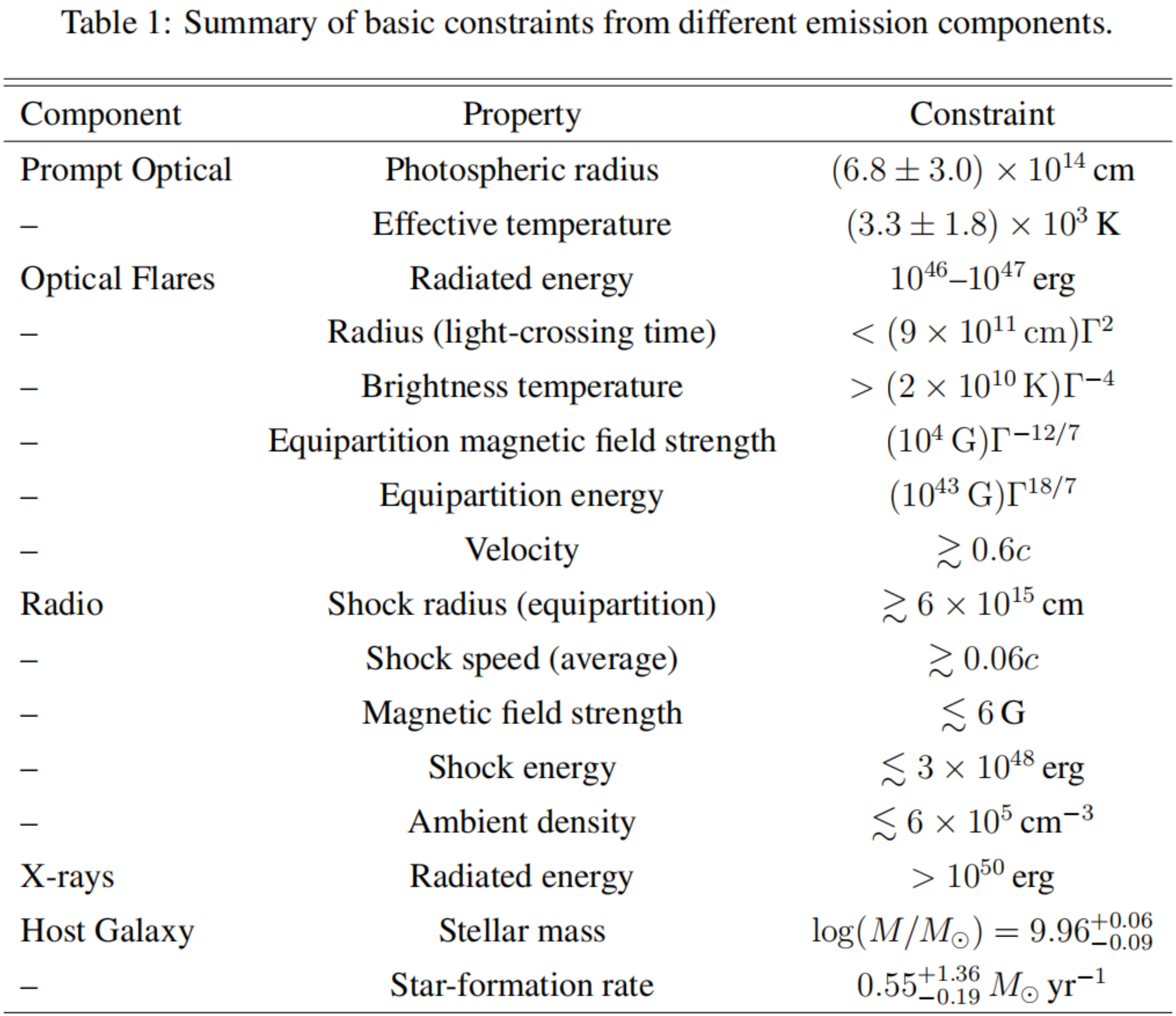


Table 1: Summary of basic constraints from different emission components.

Component	Property	Constraint
Prompt Optical	Photospheric radius	$(6.8 \pm 3.0) \times 10^{14}$ cm
–	Effective temperature	$(3.3 \pm 1.8) \times 10^{3}$ K
Optical Flares	Radiated energy	10^{46}–10^{47} erg
–	Radius (light-crossing time)	$< (9 \times 10^{11}\,\mathrm{cm})\Gamma^{2}$
–	Brightness temperature	$> (2 \times 10^{10}\,\mathrm{K})\Gamma^{-4}$
–	Equipartition magnetic field strength	$(10^{4}\,\mathrm{G})\Gamma^{-12/7}$
–	Equipartition energy	$(10^{43}\,\mathrm{G})\Gamma^{18/7}$
–	Velocity	$\gtrsim 0.6c$
Radio	Shock radius (equipartition)	$\gtrsim 6 \times 10^{15}$ cm
–	Shock speed (average)	$\gtrsim 0.06c$
–	Magnetic field strength	$\lesssim 6$ G
–	Shock energy	$\lesssim 3 \times 10^{48}$ erg
–	Ambient density	$\lesssim 6 \times 10^{5}\,\mathrm{cm}^{-3}$
X-rays	Radiated energy	$> 10^{50}$ erg
Host Galaxy	Stellar mass	$\log(M/M_{\odot}) = 9.96^{+0.06}_{-0.09}$
–	Star-formation rate	$0.55^{+1.36}_{-0.19}\,M_{\odot}\,\mathrm{yr}^{-1}$

Physical origin of the flares in AT2022tsd

- The fast timescale of the LFBOT, the luminous and variable X-ray emission, the shallow radio SED peaking in the sub-mm bands, and the characteristics of the optical flares all support the idea that AT2022tsd involves a near-relativistic outflow powered by a compact object for months.
- For the compact object, a supermassive black hole is highly unlikely given the location of AT2022tsd 6 kpc from the nucleus of a star-forming galaxy and the rapid timescale of the initial LFBOT.
- The possible power sources for the outflow are therefore the rotational spindown of a newborn neutron star, or accretion onto a stellar- or intermediate-mass compact object.
- Several models have been proposed to explain LFBOTs, and they consider three most likely ones in light of the newly discovered flares:
  - The collapse of a supergiant star
  - The merger and tidal disruption of a Wolf-Rayet star by a compact object
  - The tidal disruption of a white dwarf by an intermediate-mass black hole

Summary

- In recent years, certain luminous extragalactic optical transients have been observed to last only a few days. Their short observed duration implies a different powering mechanism from the most common luminous extragalactic transients (supernovae) whose timescale is weeks.
- Some short-duration transients, most notably AT2018cow, display blue optical colours and bright radio and X-ray emission. Several AT2018cow-like transients have shown hints of a long-lived embedded energy source, such as X-ray variability, prolonged ultraviolet emission, a tentative X-ray quasiperiodic oscillation, and large energies coupled to fast (but subrelativistic) radio-emitting ejecta.
- Here the authors report observations of minutes-duration optical flares in the aftermath of an AT2018cow-like transient, AT2022tsd.
- The flares occur over a period of months, are highly energetic, and are likely nonthermal, implying that they arise from a near-relativistic outflow or jet.
- The observations confirm that in some AT2018cow-like transients, the embedded energy source is a compact object, either a magnetar or an accreting black hole.

Thanks!