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Probing the circumstellar medium 2.8 Gyr after the big bang: detection of Bowen fluorescence in the Sunburst arc

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ABSTRACT

We discovered Bowen emission arising from a strongly lensed (i.e. with magnification factor $\mu > 20$) source hosted in the Sunburst arc at $z = 2.37$. We claim this source is plausibly a transient stellar object and study the unique ultraviolet lines emerging from it. In particular, narrow ($\sigma_v \simeq 40 \text{ km s}^{-1}$) ionization lines of Fe fluoresce after being exposed to Ly α (1216 Å) radiation that pumps selectively their atomic levels. Data from VLT/MUSE, X-Shooter, and ESPRESSO observations (the latter placed at the focus of the four UTs) at increasing spectral resolution of $R = 2500$, 11 400, and 70 000, respectively, confirm such fluorescent lines are present since at least 3.3 yr ($\simeq 1 \text{ yr}$ rest frame). Additional Fe forbidden lines have been detected, while C and Si doublets probe an electron density $n_e \gtrsim 10^6 \text{ cm}^{-3}$. Similarities with the spectral features observed in the circumstellar Weigelt blobs of Eta Carinae probing the circumstellar dense gas condensations in radiation-rich conditions are observed. We discuss the physical origin of the transient event, which remains unclear. We expect such transient events (including also supernova or impostors) will be easily recognized with ELTs thanks to high angular resolution provided by adaptive optics and large collecting area, especially in modest ($\mu < 3$) magnification regime.

Key words: gravitational lensing: strong – supernovae: general.

1 INTRODUCTION

Three main excitation mechanisms are involved in the explanation of the occurrence of bright emission lines in astrophysical sources: photoionization followed by recombination, photoexcitation to an upper level, and collisional excitation. Among the processes belonging to the second category is the Bowen fluorescence mechanism (Bowen 1934), characterized by photoexcitation by accidental resonance (PAR), i.e. the coincidence between the wavelength of a strong emission line and a transition between different atomic levels of another element.

A known example is the emission line of neutral oxygen, O I, at 8446 Å, which can be caused by a wavelength coincidence between the brights H I Ly β line (1025.72 Å) and the absorption line of O I at 1025.77 Å, followed by a successive cascade (Bowen 1947). The

Bowen fluorescence involving other elements like C, Si, Fe, and N has also been observed in various and diverse astrophysical systems such as planetary nebulae (e.g. Weymann & Williams 1969), Be stars (Merrill 1956), X-ray binary stars (e.g. McClintock, Canizares & Tarter 1975), Wolf–Rayet stars (e.g. Crowther 2007), symbiotic stars (Wallerstein et al. 1991), local Seyfert 1 nuclei and quasars (e.g. Netzer, Elitzur & Ferland 1985; Marziani et al. 2014), and nearby supernovae (Pastorello et al. 2002; Graham et al. 2017; Leloudas et al. 2019). In particular, a plethora of fluorescing emission lines in the visible and near-IR have been observed emerging from compact gas condensations located near the luminous blue variable (LBV) star of η Carinae (or η Car hereafter). Specifically, the massive and luminous star in η Car ($\gtrsim 100 M_\odot$ and $L \gtrsim 6 \times 10^6 L_\odot$) is expelling an enormous amounts of material into its surrounding, where three compact gas condensations ($N_H \simeq 10^{5-10} \text{ cm}^{-3}$, depending on the ionic diagnostics used; Hamann et al. 1999) at a distance of 10^{16} cm from the star (a few light days) have been studied in great detail. Known as the ‘Weigelt blobs’ (Weigelt & Ebersberger 1986), such

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condensations are slowly moving ($\sim 50 \text{ km s}^{-1}$) and producing many hundreds intense, narrow fluorescing emission lines including lasing emission,¹ unlike the spectrum of any other known object (Johansson & Letokhov 2007). Is it possible to observe such spectral features at cosmological distance and detect gas condensations in the vicinity of a remote massive star? Strongly lensed supernova events have been recently detected at cosmological distances (with the most spectacular case dubbed Refsdal, at $z = 1.49$; Kelly et al. 2015; Grillo et al. 2016). In this Letter, we report on the *first* detection of Bowen (fluorescent) emission from a strongly lensed candidate transient stellar object at cosmological distance ($z = 2.37$, corresponding to 2.8 Gyr after the big bang) probing circumstellar gas condensation, hosted in a giant gravitational arc known as *Sunburst* arc (e.g. Rivera-Thorsen et al. 2019). The transient stellar object we report here is highly magnified (with a magnification factor $\mu > 20$), implying that sub-regions of the arc are probed down to a few tens of parsec (Vanzella et al. 2020). We assume a flat cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 THE TRANSIENT IN THE SUNBURST ARC

An exceptionally bright ($\text{mag} \simeq 18$) gravitationally lensed multiple imaged arc at $z = 2.37$ was discovered by Dahle et al. (2016), in which several star-forming regions down to a few tens of parsec scale have been recognized. Based on the unique signature provided by the ionization leakage, Rivera-Thorsen et al. (2019) unambiguously identified one knot replicated 12 times due to strong gravitational lensing. Vanzella et al. (2020) studied in detail such a knot (dubbed A in Fig. 1) and identified other nearby additional features following the parity introduced by lensing. In particular, knot A is part of three major star-forming regions, shown in Fig. 1 as A, B, and C. It is worth noting that the identification of knots B and C is facilitated by the unambiguous 12 detections of knot A. Moreover, Fig. 1 also shows multiple images of a signature emerging in the *F160W* band (indicated with magenta arrows and following the expected parity), further confirming the identification of knot B. Consequently, also knot C fits into the global picture, following the multiplicity and parity (see Fig. 1, or appendix A of Vanzella et al. 2020). Unexpectedly, Tr appears only in the arc II, in between knots B and A (Fig. 1). Tr is spatially unresolved and has a magnitude comparable to B and A ($F814W \simeq 22$), implying that it would be easily detectable eight times, in between knots A and B. However, it is observed only one time, strongly suggesting Tr is a transient object. Another relevant quantity is the observed magnitude of Tr that lies in the range $-20.3 < M_{2000} < -18.6$, corresponding to two extremes magnifications values, $\mu = 20$ and $\mu = 100$, respectively. The first value is the minimum magnification derived in Vanzella et al. (2020) (based on geometrical arguments), the second is based on the assumption that Tr is not close to a critical line, being located within knots A and B, where no critical lines are expected. $\mu = 100$ is therefore a likely upper limit. Finally, as discussed in the next section, peculiar spectral features emerge from Tr, that, however, are not observed in any other position of the arcs.

To summarize, if Tr was not a transient, we would detect it as bright as knots A (or B) eight times, as well as its spectral features, spread over the arcs I, II, III, and IV (no significant magnification variation is expected within the triplet A, B, C). Using these arguments, we propose that Tr is plausibly a transient. As

discussed below, this interpretation is corroborated by some spectral similarity with supernovae or non-terminal transients whose ejecta interact with circumstellar material (Pastorello et al. 2002; Graham et al. 2017).

3 SPECTROSCOPIC OBSERVATIONS OF TR

Fig. 1 shows that Tr was present during *HST* imaging in February and June 2019 (P.I. H. Dahle, ID 15101). However, as discussed below, the peculiar lines associated with such a transient exist since 2016 (from MUSE DDT programme 297.A-5012(A), P.I. Aghanim) till September 2019, as our ESPRESSO observations demonstrate, implying it exists since at least 11.9 months rest frame.

3.1 VLT/MUSE, X-Shooter, and ESPRESSO observations of Tr

VLT/MUSE observations of the Sunburst arc were performed in 2016 May–August and presented in Vanzella et al. (2020), in which the Tr object was identified. Subsequently, dedicated VLT/X-Shooter observations (Prog. 0103.A-0688, P.I. Vanzella) of Tr have been acquired on 2019 May 1 and 2 to August 2 and 3 with $R = 11\,400$, and finally VLT/ESPRESSO at the focus of the four VLT/UTs was used in early September 2019 at resolution $R = 70\,000$, as part of the science verification programme of the instrument [ID 60.A-9507(A), P.I. Vanzella]. X-Shooter data were reduced with the pipeline released by ESO (Modigliani et al. 2010), following the standard approach described, e.g. in Vanzella et al. (2020). We explicitly defined the windows to extract the object and estimate the background within the slit. For the Tr object we used 2.8 ± 0.9 arcsec, with two background windows at -3.6 ± 1.0 arcsec and 0.8 ± 0.5 arcsec (positions are referred to the centre of the slit). ESPRESSO data were reduced with the data reduction software (DRS) released by ESO (Sosnowska et al. 2015) and analysed with the data analysis software (DAS) specifically developed for ESPRESSO (Cupani et al. 2019). While VLT/MUSE and X-Shooter are well tested instruments, it is worth commenting on the ESPRESSO observations. Tr with $\text{mag} \simeq 21.5$ (AB) is considered a faint target for the capabilities of the instrument, furthermore it was observed at a relatively high airmass of 1.7. Such conditions made the simultaneous centering and tracking of the target on each UT relatively challenging. Despite that, two 23-min scientific exposures were successfully acquired and reduced. The wavelength-calibrated, sky-subtracted, optimally extracted spectra of the orders produced by the DRS were combined by the DAS into a spectrum of remarkable quality, in which the continuum is detected at $S/N \simeq 3$ (per resolution element) together with several emission lines at $S/N \simeq 3\text{--}10$ (see Fig. 3). These values are in agreement with the prediction of the instrument exposure time calculator, and correspond to an estimated peak efficiency of 0.08 (including atmospheric transmission and fibre losses).

3.2 Photoexcitation by accidental resonance: Ly α pumping

The first spectral feature we noticed is the line emission at $1914 \text{ \AA}$ rest frame (see Figs 2 and 3). This line is part of the multiplet UV34, the two lowest excited configurations of Fe III, $3d^5(^6S)4s\ a^7S - 3d^5(^6S)4p\ z^7P$, which is composed by three lines 1895.473, 1914.066, and $1926.320 \text{ \AA}$ (Fig. 2 shows the Grotrian diagram). As discussed in Johansson et al. (2000) the intensity ratios of the three lines assuming a thermal population are 9:7:5 (that is the ratio of the statistical weights of the upper levels). In the present case, the $1914 \text{ \AA}$ line is detected with $S/N = 17$ and a rest-frame equivalent width of $0.56 \pm 0.05 \text{ \AA}$, and is more than 10 times stronger than the 1895

¹Lasing emission is dominated by stimulated rather than spontaneous emission.

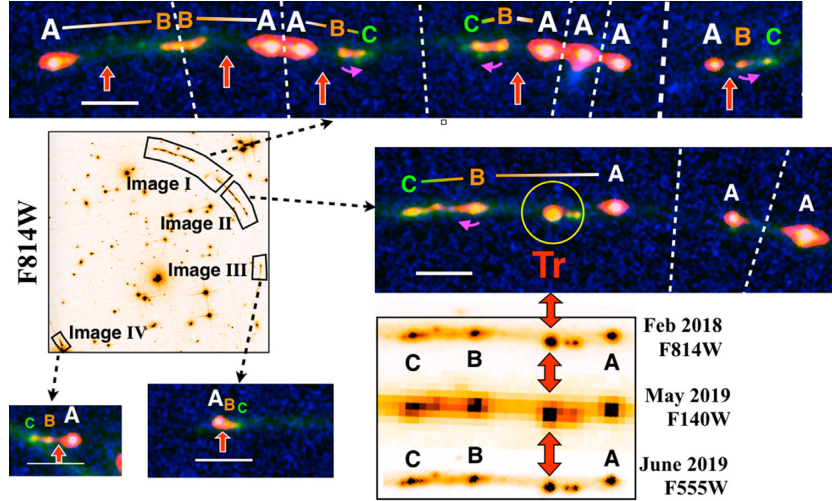


Figure 1. The four multiple arcs I, II, III, and IV are shown with RGB colour images (red = $F160W$, green = $F814W$, and blue = $F606W$), in which knots A are marked, as unambiguously identified by Rivera-Thorsen et al. (2019). Knots B and C are also identified following the expected parity introduced by lensing. The object Tr is indicated with a yellow circle and its expected multiple images located between knots A and B are marked with red arrows. A non-transient object would appear eight times and as bright as knot A. Magenta small arrows mark a feature emerging from the red band, $F160W$, only on one side of knot B. Such a tail replicates accordingly to multiple images (presence) and parity (orientation). The bottom-right panel shows the location of Tr split over multi-epoch *HST* observations, from 2018 February to 2019 June.

Photoexcitation by Accidental Resonance (PAR)

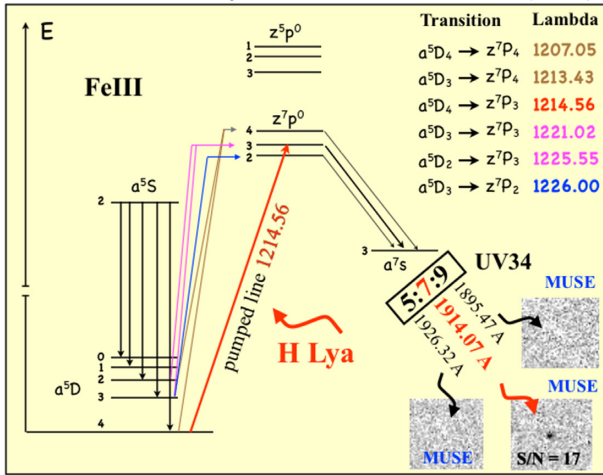


Figure 2. The Grotrian diagram showing the PAR emission from the triplet of Fe III UV34 (adapted from Johansson et al. 2000), with indicated the relative ratios among the three lines in the case of not Ly α pumping (5:7:9, see text). On the top-right, the wavelengths of the transitions are reported (also shown with the same colour in the diagram). In the bottom-right, the three continuum-subtracted MUSE slices ($d\nu = 300 \text{ km s}^{-1}$), showing the three wavelengths of UV34, among which only the 1914.07 Å line emerges, with rest-frame equivalent width of $0.56 \pm 0.05 \text{ Å}$.

and 1926 Å lines (Figs 2 and 3), which suggests a PAR effect is in place, selectively exciting the z^7P_3 level. Such emission mechanism has also been detected and deeply investigated by Johansson et al. (2000) for the case of η Carinae, in which the same iron line 1914 Å is selectively excited by H Ly α photons. If the excitation was continuum fluorescence, two lines in UV34 would be observed and in the case of collisional excitation or recombination all three lines would appear. The UV34 multiplet of Fe III can thus be used for determining whether the excitation source is blackbody

radiation with substantial flux around 1216 Å or substantial spectral compression due to H Ly α radiation pumping a single channel.

The presence of additional fluorescence Ly α -pumped iron lines at 2400–2500 Å corroborates such an interpretation. In particular, Zethson et al. (2012) identify more than 2500 lines emerging from dense gas condensation (Weigelt blobs) in the proximity of the hot star in η Car, several of them identified as fluorescent Ly α pumped transitions. Besides the aforementioned Fe III 1914 Å, we find additional Fe II Ly α -pumped lines in Fe II and Fe III. Fig. 3 shows four of them, 2419, 2439, 2464, and 2507–2509 Å, detected in the 2016 MUSE observations (at resolution $R = 2500$), and still present in 2019 X-Shooter observations (at $R = 11\,400$). These lines are only observed in Tr.

Additional forbidden [Fe III] lines are detected at 2483 and 2495 Å rest frame from the multiplet $3d^6 \text{ } ^3D_4 - 3d^5(^6S)4s \text{ } a^5S$. Two additional lines of the multiplet are the 2438 and 2465 Å, blending with the fluorescent lines discussed above. The line ratios of C III] $\lambda\lambda$ 1907, 1909 Å and Si III] $\lambda\lambda$ 1883, 1892 Å provide a measurement of the electron density n_e . In the spectrum of Tr the blue components of both doublets are absent, implying 3σ limits of <0.07 and <0.04 for 1883/1892 and 1907/1909 line ratios, respectively. Such values correspond to $n_e \gtrsim 10^6 \text{ cm}^{-3}$ (e.g. Maseda et al. 2017). We note that such high density is reminiscent of what measured in the Weigelt blobs nearby the LBV star of η Car, where a mixture of dozens fluorescent and forbidden lines are detected (Zethson et al. 2012).

It is worth noting that Johansson, Hartman & Letokhov (2006) explained the Si III] λ 1892 emission observed in η Car as due to the resonance-enhanced two-photon ionization (RETPI) mechanism, that is the combination of H Ly α (1216) and H Ly β pumping. They also suggest that such a two-photon process naturally explains the absence of the blue component of the silicon doublet (Si III] λ 1883), as due to a gA value (Einstein transition probability) six order of magnitude smaller than Si III] λ 1892. It is not clear if the same is happening on Tr, for which the Si III] λ 1883 is absent, too; further investigation is needed and a proper monitoring of the time variability of the line would be needed. Therefore, the RETPI mechanism for silicon remains a possibility.

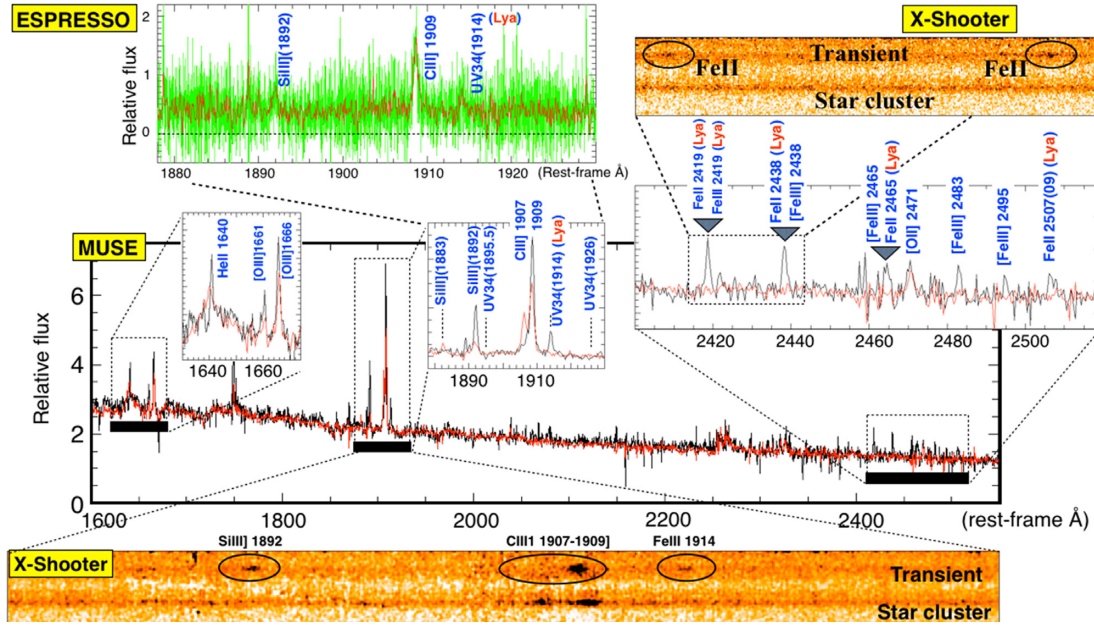


Figure 3. A collection of the VLT/MUSE, X-Shooter, and ESPRESSO spectroscopic observations in the ultraviolet portion of the spectrum. In the main panel with thick axis, the MUSE spectrum (obtained in June 2016) at $R = 2500$ of the star cluster (knot A, red line) and the transient (Tr, black line) are shown, with the insets blowing up the regions around the fluorescence lines due to H Ly α pumping (see text for details). The two-dimensional X-Shooter data (obtained in May 2019) are also shown with resolution $R = 11\,400$. The one dimensional spectrum at $R = 70\,000$ obtained with ESPRESSO during 2019 September at the focus of the four VLT/UTs is shown in the top-left (the green/red line corresponds to $R = 70\,000/7000$). The Fe Ly α pumped lines are marked with a red label.

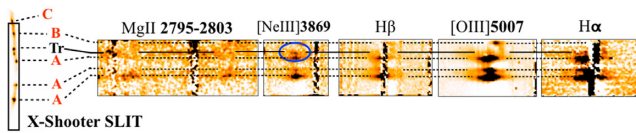


Figure 4. Additional atomic transitions are shown, extracted from X-Shooter VIS and NIR arms. On the left side, the 11 arcsec X-Shooter slit is shown. For the knots A (the star cluster) and B, elements like Mg, Ne, H β , O, and H α are detected in emission. For the transient (Tr) only Ne III $\lambda 3869$ is clearly identified, despite the seeing limited X-Shooter observations, while the other lines are not identified. Ne III $\lambda 3869$ is marked with a blue ellipse. On the left the *HST*/F814W image with the X-Shooter slit are shown.

4 DISCUSSION

From the above considerations, it turns out that Tr is likely a transient compact source, relatively bright with $-20.3 \text{ mag} < M_{2000} < -18.6 \text{ mag}$. Although the absolute magnitude of Tr is not securely determined, it lies in a range that is typical of luminous SN explosions (Richardson et al. 2014), while non-terminal eruptions of LBVs or other massive stars are expected to be fainter than -15 mag (Van Dyk et al. 2000; Maund et al. 2006). Furthermore, the spectra of Tr show fluorescent (Ly α pumped) and forbidden Fe emission lines in a relatively dense regime. Interestingly, these fluorescence lines visible in the UV domain have been previously observed in some SNe with evidence of strong interaction between the ejected gas and pre-existing circum-stellar material (CSM). Usually, these SNe have spectra dominated by narrow (FWHM from a few tens to a few hundred km s^{-1}) H lines in emission, and are hence labelled as Type II n SNe. For instance, the UV lines observed in the spectra of Tr (including Ne III $\lambda 3869 \text{ \AA}$, see Fig. 4), were

also found in the *HST* UV spectra of the Type II n SNe 1995N (Fransson et al. 2002) and 2010jl (Fransson et al. 2014). However, it appears there is a deficiency of the Balmer lines H α and H β (Fig. 4).

The long-lasting light curve of Tr (at least 1 yr in rest frame) is typical of SNe interacting with their CSM or even long-duration giant eruptions of LBV stars. In addition, the FWHM of the fluorescence lines ($\simeq 85 \text{ km s}^{-1}$) is consistent with the expansion velocity expected in the wind of an LBV. So, this would be an argument suggesting that Tr is a long-duration eruption of a massive star, or even produced by a terminal stellar explosion in a hydrogen-rich circumstellar medium. Although this explanation is not corroborated by a clear detection of Balmer lines in the Tr spectrum (see Fig. 4), the detection of He II $\lambda 1640 \text{ \AA}$ provides support to the CSM-interacting SN scenario. He II lines in the optical domain are occasionally detected in young core-collapse SNe exploding inside a circumstellar shell (Khazov et al. 2016).

The absence of the Balmer lines as well as Mg II $\lambda 2800 \text{ \AA}$ in the X-Shooter spectrum of Tr is puzzling. These lines are in fact expected in the spectrum of an H-rich ejecta-CSM interacting transient (e.g. Fransson et al. 2005). Alternatively, we are observing a lensed H-poor interacting SN. SN Ibn (e.g. Pastorello et al. 2016) are well-known SNe interacting with a He-rich and H-deprived CSM whose spectra are dominated by relatively narrow and prominent He I features in emission. While these lines are not unequivocally observed in the Tr X-Shooter spectrum, He II $\lambda 1640 \text{ \AA}$ is clearly detected in the June 2016 MUSE spectrum. In general, the He II lines persist for a short period in SN spectra (e.g. Pastorello et al. 2015; Gangopadhyay et al. 2020), and this may explain their non-detection in 2019. We also know that some ultrastripped core-collapse SNe may be powered by ejecta-CSM interaction without necessarily showing H or He I lines. For instance, this scenario has been proposed for some superluminous

SNe (e.g. Moriya, Sorokina & Chevalier 2018) or in pulsational pair-instability events (Woosley 2017). However, these transients should at least show prominent [O I] 6300, 6364 Å, along with a blend [Ca II]/[O II] at around 7300 Å. In summary, the nature of Tr is still unclear, although the presence of the object over the last year (in the rest-frame) and the similarity of the UV spectrum of Tr with those of some interacting transients, most likely indicate an SN whose ejecta is interacting with some hydrogen-poor CSM. The future monitoring of the light curve will be crucial to address the physical origin of this transient.

Regardless of its true nature, Tr demonstrates that the indirect detection of a gas condensation in the vicinity of a massive star at cosmological distance is feasible with gravitational lensing, even without the extremely high spatial resolution (i.e. of the order of a few light days), which would be required to observe it directly. Whether the gas condensation in Tr is exposed to an external field with emission covering several Lyman series or it is invested by Lyman continuum that induces *in situ* transitions within the condensation itself remains to be understood.

In conclusion, Tr is well recognized as an individual point-like object thanks to strong gravitational lensing, that is known to probe a limited volumes (e.g. Shu et al. 2018). However, future adaptive optics facilities (like E-ELT or VLT/MAVIS) will have enough angular resolution to detect even in blank field objects that are currently observable only in lensed fields (with $\mu \sim 15\text{--}20$), but embracing a much larger volume (a factor 10 larger than lensing) in the redshift range $1 < z < 8$, accessing absolute magnitudes down to ~ -17 . This suggests that, potentially, cases like Tr will be easily recognizable in the future.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author. They are also available as raw data at the European Southern Observatory archive under the programme IDs 0103.A-0688, 60.A-9507, and 297.A-5012, and *HST* archive under proposal ID 15101.

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