A transient optical laser at cosmological distance probes the circum-stellar material 2.8 Gyr after the Big Bang

E. Vanzella\textsuperscript{1,*†}, M. Meneghetti\textsuperscript{1}, A. Pastorello\textsuperscript{2}, F. Calura\textsuperscript{1}, E. Sani\textsuperscript{3}, G. Cupani\textsuperscript{4}, G.B. Caminha\textsuperscript{5}, M. Castellano\textsuperscript{6}, P. Rosati\textsuperscript{7,1}, V. D’Odorico\textsuperscript{4}, S. Cristiani\textsuperscript{4}, C. Grillo\textsuperscript{8}, A. Mercurio\textsuperscript{9}, M. Nonino\textsuperscript{4} and G.B. Brammer\textsuperscript{10}

\textsuperscript{1}INAF – Osservatorio di Astrofisica e Scienza dello Spazio, via Gobetti 93/3, 40129 Bologna, Italy
\textsuperscript{2}INAF – Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, 35122, Padova, Italy
\textsuperscript{3}European Southern Observatory, Alonso de Cordova 3107, Casilla 19, Santiago 19001, Chile
\textsuperscript{4}INAF – Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, I-34143, Trieste, Italy
\textsuperscript{5}Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV Groningen, The Netherlands
\textsuperscript{6}INAF – Osservatorio Astronomico di Roma, Via Frascati 33, I-00078 Monte Porzio Catone (RM), Italy
\textsuperscript{7}Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, via Saragat 1, I-44122 Ferrara, Italy
\textsuperscript{8}Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy
\textsuperscript{9}INAF – Osservatorio Astronomico di Capodimonte, Via Moiariello 16, I-80131 Napoli, Italy
\textsuperscript{10}Cosmic Dawn Center, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark

ABSTRACT
We discovered Bowen emission arising from a strongly lensed ($\mu > 20$) transient stellar object hosted in the Sunburst arc at $z=2.37$. Unique ultraviolet lines emerge at the location of the transient. In particular, narrow ($\sigma_v \simeq 40$ km s$^{-1}$) ionisation lines of several chemical species (Fe, C, Si) fluoresce after being exposed to Lyman series (e.g., Ly$\alpha$, Ly$\beta$) of H, He$^+$ and He$^++$ that pump selectively their atomic levels. Similarities with the Resonance-Enhanced Two Photon-Ionisation (RETPI) spectral features observed in the circum-stellar Weigelt blobs of Eta Carinae are observed. Data from VLT/MUSE, X-Shooter and ESPRESSO observations (the latter placed at the focus of the four UTs) at increasing spectral resolution of $R=2500$, 11400 and $R=70000$, respectively, confirm the lasing action since at least 3.3 years ($\simeq 1$ year rest-frame), and probe the circum-stellar dense gas condensations in radiation-rich conditions. 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 recognised with ELTs thanks to high angular resolution provided by adaptive optics and large collecting area, especially in modest ($\mu < 3$) magnification regime.

Key words: (stars:) supernovae: general – gravitational lensing: strong

1 INTRODUCTION
Three excitation mechanisms are mainly involved in the explanation of the occurrence of bright emission lines in astrophysical sources: photoionization (or excitation to n upper level) followed by recombination, collisional excitation, and the Bowen mechanism (Bowen 1934, 1935). The latter is generated by photoexcitation by accidental resonance (PAR), i.e. the coincidence between the wavelength emission of a given element and a transition between different atomic levels of another element.

A known example is the emission line of neutral oxygen, O$_i$, at 8446Å, which can be caused by a wavelength coincidence between the brights H$_i$ Ly$\beta$ line (1025.72Å) and the absorption line of O$_i$ at 1025.77Å, followed by a successive cascade (Bowen 1947). The Bowen fluorescence involving other elements like C, Si, Fe, 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 et al. 1975), Wolf-Rayet stars (e.g., Crowther 2007), symbiotic stars (Wallner et al. 1991), local Seyfert 1 nuclei and quasars (e.g., Marziani et al. 2014; Netzer et al. 1985), and...
Figure 1. In the top row, form left to right: the HST F814W band of the fours arcs, indicated with red boxes; the narrow-band MUSE data at 1914 Å and CⅢλ1909 rest-frame, with the emission from the Tr (transient) marked with red circles. Black arrows show the arcs in which such emission should simultaneously lie, if it was not a transient. In the bottom the zoomed regions of arcs I, II and III are shown at three different epochs: future, past and present. The transient Tr is indicated with red arrows and appears only in II. The three knots A, B and C, are also labelled.

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 (≥100M⊙ and L ≥ 6×10⁶L⊙) is expelling an enormous amounts of material into its surrounding, where three compact gas condensations (N_H > 10²⁶ cm⁻³) at a distance of 10¹⁶ cm from the star (a few light days) have been studied in great detail. Known as “the Weigelt blobs” (Weigelt, & Ebersberger 1986), such condensations are slowly moving (∼50 km s⁻¹) and producing many hundreds intense, narrow fluorescing emission lines including lasing emission¹, unlike the emission of any other known object (Johansson, & Letokhov 2007). Remarkably, the emerging lasing spectrum from η Car probes physical scales in the surrounding of single massive stars. 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 lasing emission from a strongly lensed transient stellar object at cosmological distance (z=2.37, 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 (µ > 20 – 50), 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 Ω_M = 0.3, Ω_L = 0.7 and H₀ = 70 km s⁻¹ Mpc⁻¹.

2 THE TRANSIENT IN THE SUNBURST ARC

An exceptionally bright (mag ≃ 18) gravitationally lensed multiple imaged arc 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 recognised. One of them has also been confirmed to show Lyman continuum leakage (split over 12 multiple images, Rivera-Thorsen et al. 2019), arising from hot and massive stars hosted in a gravitationally-bound young massive star cluster of a few 10⁶ M⊙, with an effective radius not larger than 20 parsec (Vanzella et al. 2020), and with an age and metallicity of 3 Myr and 0.5 Z⊙, respectively (Chisholm et al. 2019). Vanzella et al. (2020) identified such cluster as knot A, as part of three major star-forming regions hosted by the galaxy at z=2.37 (see their appendix A). Figure 1 summarizes the HST images of the multiple arc and star-forming knots. In particular, the triplet (A, B, C) is detected over the arcs II, III and IV showing a different stretch. Such a system (together with other multiple features) provides constraints on the location of the critical line, and follows the expected mirroring pattern dictated by strong lensing (see appendix A of Vanzella et al. 2020). Conversely, the bright (magnitude 21.5 in the F814W band) and spatially unresolved knot dubbed Tr in Figure 1, appears only in the arc II, in between knots B and A. Tr has a magnitude comparable or brighter than B and A, implying that it would be easily detectable on the other multiple images on arcs III and IV. However, it is not observed.

To confirm the transient nature we would need to monitor this object over time. However, since it is in a multiply imaged source, lensing can be very helpful to test this hypothesis. Indeed, photons traveling along different trajectories through the lens gravitational potential accumulate different time delays. Therefore, the transient should appear at different times in the source multiple images, specifically in images II, III, and IV. In a gravitational lensing event, multiple images form at the stationary points of the so-called time-delay surface. The shape of this surface depends on the source intrinsic position and on the shape of the projected gravitational potential of the lens. It is not the scope of this work to provide detailed predictions of time delays between arcs (a lens model will be developed in a dedicated work), however image III is located at the absolute minimum of the cluster time delay surface for the source producing the sunburst arc. Also image I is at a local minimum of the time delay surface, which however is a local minimum, and corresponds to a larger time delay with respect to image III. Instead, image II is at a saddle point of the time-delay surface, as well as image IV. Thus, the arrival time of the light emitted by the source is expected to follow the order III, II and IV, therefore probing three distinct epochs. In particular, we expect the event will appear in arc IV sometime in the future. If Tr was not a transient, we would detect a knot as bright as knots A, B in both arcs III and IV (no significant magnification variation is expected within the triplet A, B, C, since its integrity is preserved). Using these arguments, we

¹ Lasing emission is dominated by stimulated rather than spontaneous emission.
3 AN ASTROPHYSICAL LASER DETECTED AT COSMOLOGICAL DISTANCE

Figure 1 shows that Tr was present during HST imaging in February and June 2019 (PI: H. Dahle, ID 15101). However, as discussed below, the peculiar lines associated to such a transient exist since 2016 (from MUSE DDT programme 297.A-5012(A), PI: 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 May-August 2016 and presented in Vanzella et al. (2020), in which the Tr object was identified. Subsequently, dedicated VLT/X-Shooter observations (Prog. 0103.A-0688, PI Vanzella) of Tr have been acquired on 1-2 May - 2-3 August 2019 with R=11400, and finally VLT/ESPRRESSO at the focus of the four VLT/UTs was used in early September 2019 at resolution R=70000, as part of the science verification program of the instrument (ID 60.A-9507(A), PI Vanzella). X-Shooter data were reduced following standard procedures as described in, e.g., Vanzella et al. (2020) and the 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 mag $\approx$ 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-minutes 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 $\approx$ 3 (per resolution element) together with several emission lines at S/N $\approx$ 3-10 (see Figure 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 fiber losses).

3.2 Photoexcitation by Accidental Resonance (PAR) of Fe III UV34 multiplet

The first spectral feature we noticed is the line emission at 1914Å rest-frame (see Figure 1, 2 and 3). This line is part of the multiplet UV34 located around 1900Å arising from the FeII 17th excited level ($S_3$), the two lowest excited configuration of FeIII, $3d^5(3S)4s\,5\,P$, which is composed by three lines 1895.473Å, 1914.066Å and 1926.320Å (Figure 2 shows the Grotrian diagram). As discussed in Johansson et al. (2000) the intensity ratios of the three lines assuming a thermal population is 9:7:5 (that is the ratio of the statistical weights of the upper levels). In the present case, the 1914Å line is detected at S/N=17 and a rest-frame equivalent width of 0.56 ± 0.05Å, and is more than 10 times stronger than the 1895Å and 1926Å lines (Figures 2 and 3), which implies a Photoexcitation by Accidental Resonance (PAR) effect, selectively exciting the $z^2P_3$ level. Such emission mechanism has been also detected and deeply investigated by Johansson et al. (2000) for the case of η Carinae, in which the same iron line 1914Å is selectively excited by H Ly$\alpha$. The UV34 multiplet of FeIII can thus be used for determining whether the excitation source is blackbody radiation with substantial flux around 1215Å or substantial spectral compression due to H Ly$\alpha$ radiation pumping a single channel.

3.3 Additional fluorescence from other elements

More than 2500 lines have been identified in dense gas condensations (Weigelt blobs) surrounding the very LBV star of η Carinae, in which many of them are fluorescent lines pumped by H Ly$\alpha$ (Zethson et al. 2012). In particular, additional fluorescent FeII lines pumped by H Ly$\alpha$ photons appear in the 2400-2500Å region of the η Car spectrum. Figure 3 shows the same lines detected with MUSE on Tr during 2016 (with spectral resolution R=2500) and with X-Shooter during 2019 (with R=11400). Similarly, Johansson et al. (2006) explained the SiII[1892] emission in η Car as due to the Resonance-Enhanced Two-Photon Ionisation (RETPI) mechanism, that is the combination of
H Lyα (1216) and H Lyβ pumping. They also suggest that such a two-photon process naturally explains the absence of the blue component of the silicon doublet (Si iii λ1883). The detection of the single Si ii λ1892 line in Tr, with absence of the blue component (1892/1883 > 30, Figure 3) suggests fluorescence in Tr is in place also for silicon. Interestingly, other light elements can fluoresce by means of the RETPI process. Johansson, & Letokhov (2007) analysed the chains of a few of them, e.g., carbon, nitrogen, oxygen, neon and argon atoms and successive ions of these elements when exposed to pairs of spectral Lyman lines with progressively increasing photon energies: H i + H i, H i + He i, H i + He i + H i, and He i + He i. For example the RETPI scheme for carbon provides a path to C v, C iv → C iii → C i → C, in which C iii (24.38 eV) arises from C ii with the combination of He i Lyα (584 Å), He i Lyβ (537 Å), H Lyβ (1026 Å) and H Lyα (1215 Å) (Johansson, & Letokhov 2007). Remarkably, the prominent C ii λ1909 emission component observed on Tr and the absence of its blue component (C ii λ1909) is even more evident than silicon (C ii λ1907 / C ii λ1909 < 0.05, see Figure 3), suggesting – as for silicon – that carbon might undergo the similar RETPI scheme as described above. In practice, once the fluorescence mechanisms is in place, it might involve various atomic species. For example the Ne iii λ3869 emission line is the only one emerging in the X-Shooter/NIR arm (see below, and Figure 4), and possibly undergoing RETPI by H Lyα (1215 Å) and He i Lyα (303 Å) (Johansson, & Letokhov 2007).

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, the MUSE spectrum at R=2500 of the star cluster (knot A, indicated with the red line) and the transient (Tr, indicated with the black line) are shown, with the insets blowing up the regions around the fluorescence lines due to H Lyα pumping (see text for details). The corresponding two-dimensional X-Shooter spectra are also shown with resolution R=11400. The one dimensional spectrum at R=70000 obtained with ESPRESSO at the focus of the 4 VLT/UTs is shown in the top-left (the green/red line corresponds to R=70000/7000). The Fe iii UV34 1914 Å emission is present in all spectra of Tr.

4 DISCUSSION

The fluorescent phase Tr is undergoing is likely to be dominated by both PAR and RETPI emission, as indicated by the Fe UV34 triplet, the group of Fe lines in the range 2400-2500 Å and from the absence of blue components of two prominent emission lines, Si ii λ1892 and C ii λ1909 (Figures 2 and 3). 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 IIn SNe. For instance, the UV lines observed in the spectra of Tr (including Ne iii λ3869), were also found in the HST UV spectra of the Type IIn SNe 1995N (Fransson et al. 2002) and 2010jl (Fransson et al. 2014). However, it appears there is a deficiency of the Balmer lines Hα, Hβ (Figure 4).

The long-lasting light curve of Tr (at least 1 year 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 (≈ 85 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. However, this explanation is not corroborated by
a clear detection of Balmer lines in the Tr spectrum (see Figure 4).

While the emitting mechanisms is clear (PAR and RETPI) and localised in a possibly small and dense gas condensation, the next question is what source is generating such radiation-rich spectral lines. The absence of the condensation, the next question is what source is generating such radiation-rich spectral lines. The absence of the Tr lines as well as Mg lines 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. 2015) are well-known SNe interacting with a He-rich and H-deprived CSM. However, their spectra are dominated by relatively narrow and prominent H features in emission, which are not unequivocally observed in the Tr spectrum. We also know that some ultra-stripped core-collapse SNe may be powered by ejecta-CSM interaction without necessarily showing H or He lines. For instance, this scenario has been proposed for some super-luminous SNe (e.g., Moriya et al. 2018) or in pulsational pair-instability events (Woosley 2017). However, these transients should at least show prominent [OⅡ] 6300,6364 Å, along with a blend [CⅢ]/[OⅡ] at around 7300 Å. In summary, the nature of the Tr is still unclear, although the slow-declining light curve and the similarity of the UV spectrum of Tr with those of some SNe IIn seem to favour some sort of ejecta-CSM interacting transient. 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 gas condensation in the vicinity of a remote massive star at cosmological distance is feasible with gravitational lensing, even without having access to high spatial resolution for direct observation of such a spatial structure (e.g., few light days). Weather 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 Lyman lines within the condensation itself remains to be understood.

Finally, it is worth mentioning that Tr is well recognised as an individual point-like object thanks to strong gravitational lensing effect, that is known to probe a limited volume if compared to non-lensed fields (e.g., Shu et al. 2018). However, future facilities AO-assisted (like E-ELT or VLT/MAVIS) will have enough angular resolution to mimic current HST lensed images (those with μ ∼ 15 – 20), but embracing a much larger volume (a factor 10 larger then lensing) in the redshift range 1 < z < 8, accessing absolute magnitudes down to ~ −17, suggesting that, potentially, cases as Tr will be easily recognisable in the future, opening for the possibility to commonly probe the circum-stellar material at cosmological distance.

ACKNOWLEDGMENTS

This work is supported by PRIN-MIUR 2017 WSCC32. We acknowledge funding from the INAF main-stream (1.05.01.86.31). GBC acknowledges funding from the ERC Consolidator Grant ID 681627-BUILDUP. We thank A. Comastri for useful discussions. GB acknowledges funding for the Cosmic Dawn Center provided by the Danish National Research Foundation under grant No. 140.

REFERENCES

Bowen, I. S. 1934, PASP, 46, 146
Bowen, I. S. 1935, ApJ, 81, 1
Bowen, I. S. 1947, PASP, 59, 196

Chisholm, J., Rigby, J. R., Bayliss, M., et al. 2019, ApJ, 882, 182
Capani, G., D’Odorico, V., Cristiani, S., et al. 2019, Astronomical Data Analysis Software and Systems XXVI, 362
Crowther, P. A. 2007, ARA&A, 45, 177
Dahle, H., Aghanim, N., Guennou, L., et al. 2016, A&A, 590, L4
Fransson, et al. 2002, ApJ, 572, 350
Fransson, C., Ergon, M., Challis, P. J., et al. 2014, ApJ, 797, 118
Fransson, C., et al. 2005, ApJ, 622, 991
Graham, M. L., et al. 2017, MNRAS, 469, 1559
Grillo, C., Karmann, W., Suyu, S. H., et al. 2016, ApJ, 822, 78
Johansson, S., Zethson, T., Hartman, H., et al. 2000, A&A, 361, 977
Johansson, S., Hartman, H., & Letokhov, V. S. 2006, A&A, 452, 253
Johansson, S., & Letokhov, V. S. 2007, New Astron. Rev., 51, 443
Kelly, P. L., et al. 2015, Science, 347, 1123
Leloudas, G., et al. 2019, ApJ, 887, 218
Marziani, P., Martínez-Aldama, M. L., Dultzin, D., Sulentic, J. W. 2014, The Astronomical Review, 9, 29
McClintock, J. E., Canizares, C. R., & Tarter, C. B. 1975, ApJ, 198, 641
Merrill, P. W. 1956, J. R. Astron. Soc. Canada, 50, 184
Moriya, T. J., Sorokina, E. I., & Chevalier, R. A. 2018, Space Sci. Rev., 214, 59
Netzer, H., Elitzur, M., & Ferland, G. J. 1985, ApJ, 299, 752
Pastorello, A., et al. 2002, MNRAS, 333, 27
Pastorello, A., et al. 2015, MNRAS, 449, 1941
Rivera-Thorsen, T. E., et al. 2019, Science, 366, 738
Shu, Y., Bolton, A. S., Mao, S., et al. 2018, ApJ, 864, 91
Sosnowska, D., Lovis, C., et al. 2015, Astronomical Data Analysis Software an Systems XXIV (ADASS XXIV), 285

MNRAS 000, 000–000 (0000)
