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Letter to the Editor

GN-z11: Witnessing the formation of second-generation stars and an accreting massive black hole in a massive star cluster

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ABSTRACT

We explore the possibility of the *N*-rich young proto-galaxy GN-z11, recently observed at $z = 10.6$ by JWST, being the result of the formation of second generation stars from pristine gas and asymptotic giant branch (AGB) ejecta in a massive globular cluster or nuclear star cluster. We show that a second generation forming out of gas polluted by the ejecta of massive AGB stars and mixed with gas of a standard composition accounts for the unusually large N/O in the GN-z11 spectrum. The timing of the evolution of massive (4–7.5 $M_\odot$) AGBs also provides a favorable environment for the growth of a central stellar mass black hole to the AGN stage observed in GN-z11. According to our model, the progenitor system was born when the age of the Universe was ≃260−380 Myr, well within the bounds of the pre-reionization epoch.

Key words. stars: AGB and post-AGB – stars: black holes – galaxies: clusters: general – galaxies: formation – galaxies: high-redshift

1. Introduction

Recent observations of GN-z11 have unexpectedly opened up a new window onto our knowledge of the first phases of evolution of the Universe. The precise redshift measurement of $z = 10.603$ from JWST/NIRSpec (Bunker et al. 2023) has established its age as 430 Myr in the ΛCDM model, based on the determination of cosmological parameters from Planck Collaboration VI (2020). In the JADES NIRCam imaging (Tacchella et al. 2023), this object shows an intrinsic half-light radius of only $0.0016 \pm 0.005''$ (64 ± 20 pc), suggesting that it may host a possible globular cluster (GC) in formation (Senchyna et al. 2023; Belokurov & Kravtsov 2023). This young age is puzzling, as the spectrum reveals a very high nitrogen abundance, which has not been seen at similar metallicity in the nearby Universe (e.g., Izotov et al. 2012, 2023), nor predicted by standard chemical evolution models (e.g. Vincenzo et al. 2016), while a high [N/O] is consistent with the abundances in the "anomalous" globular cluster stars, suggesting that we may be witnessing the formation of their "second generation" (Charbonnel et al. 2023; Renzini 2023; Marques-Chaves et al. 2023).

Cameron et al. (2023) quantified the relative abundances of C, N, and O from the spectrum of GN-z11 and provided error boxes for both "fiducial" abundances and for more "conservative" assumptions. In both cases, the most relevant result is the lower limit to the nitrogen-to-oxygen ratio, $\log(N/O) > -0.25$ (a value that is also compatible with the determination from detailed nebular models by Senchyna et al. 2023), which is more than one order of magnitude higher than the values found in galaxies of a similar low metallicity ($\log(O/H)+12 \lesssim 8.0$) at low redshift and also larger than the solar value ($\log(N/O) = -0.8$). The nitrogen and oxygen content observed in star-forming galaxies in the Local Universe is aptly reproduced by chemical evolution models (Vincenzo et al. 2016), while very ad hoc assumptions should be made to account for such an anomalous and fast nitrogen increase observed in the spectrum of the young and compact GN-z11 (Bekki & Tsujimoto 2023; Nagele & Umeda 2023; Kobayashi & Ferrara 2023). Nevertheless, these same abundances are common among a great fraction of the stars of globular clusters (GC), where indeed peculiar abundance patterns apparently emerged very early in the life of the Universe, whereby the gas had been processed by proton capture reactions at high temperatures ($T > 40$ MK), leaving the signatures of full CNO processing and of the Ne–Na and Mg–Al chains (e.g., Gratton et al. 2019). The main process invoked in the formation of GC "multiple populations" is that this hot H-burning occurs inside the stars formed at first in the cluster and that the products of these nuclear reactions, collected and mixed with non–processed gas, formed a "second generation", which typically represents the most abundant component (from ∼45% to 90% of stars, see e.g., Milone & Marino 2022) of today's GCs. Thus,

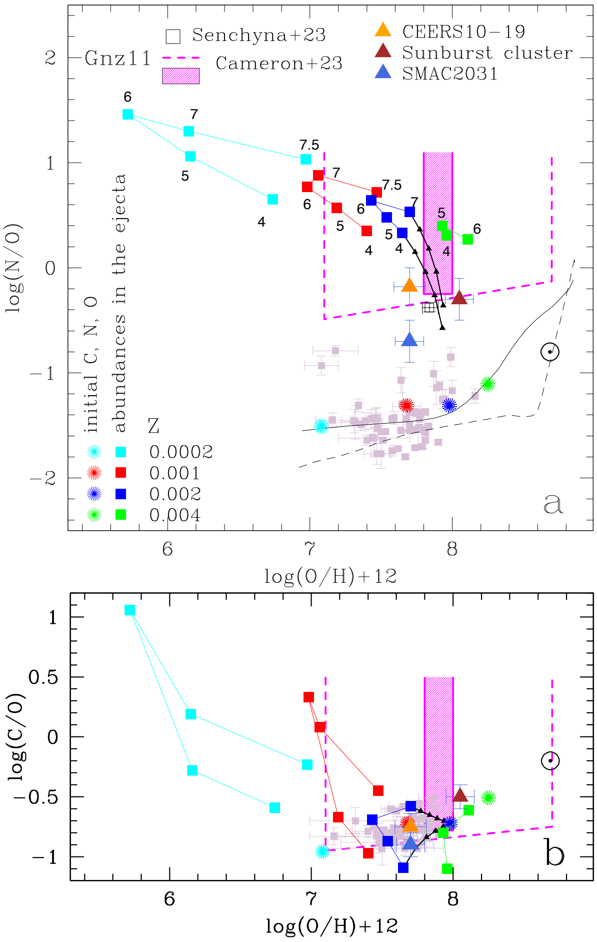

Fig. 1. Abundances in GN-z11 and other objects, compared with models. Panel a: diagram log(N/O) versus log(O/H)+12: "fiducial" (pink filled) and "conservative" (pink dashed border) error boxes for GN-z11 (Cameron et al. 2023). Black open square with error bars: abundances from Senchyna et al. (2023). Colored squares: average abundances ratios in the ejecta of intermediate mass AGB stars (Ventura et al. 2013). Metallicities in mass fraction Z and masses (from 7.5 to 4 $M_{\odot}$) are labelled in the figure. Asterisks: initial O/H and N/O abundances of the models (see Table 1 and Ventura et al. 2013). Solar symbol is placed at the values corresponding to solar abundances. Black lines: examples of dilution of the ejecta (of the 4 and 7 $M_{\odot}$ at Z = 0.002) with gas having the initial chemical composition; triangles are marking 20, 40, 60 and 80% of diluting pristine gas. Thistle squares with error bars: abundances observed in low metallicity galaxies at z = 0.3–0.4 (Izotov et al. 2023) and in the local compact galaxies from the SLOAN (Izotov et al. 2012). At the bottom: upper (full) and lower (dashed) envelope of the chemical evolution models by Vincenzo et al. (2016). Other star forming galaxies at high redshift having high log(N/O) are shown as colored triangles and are identified in the labels. Panel b: diagram log(C/O) versus log(O/H)+12. Symbols and lines as in panel a.

the birth of the second generation is a major event in the star formation history of GCs.

Similarly, high N/O abundances are found (see Fig. 1) in a few other star-forming objects at lower resdshift, CEERS-1019 at $z \sim 8.7$ (Isobe et al. 2023), the super star cluster in the Sunburst galaxy (Pascale et al. 2023; at z = 2.67), a galaxy at z = 3.5 lensed by the cluster SMACS2031, the Lynx arc at z = 3.37 (Marques-Chaves et al. 2023). For some of these objects as well, it has been suggested that they could be hosting the formation of second generation in GCs (Isobe et al. 2023; Marques-Chaves et al. 2023). Although a high N/O ratio is an important feature characterizing the abundances in the second generation stars in GCs, it can result from a variety of mass-loss events where CNO cycled material is expelled, such as stages of massive Wolf-Rayet stars (Limongi & Chieffi 2018; Kobayashi & Ferrara 2023), common envelope, or other forms of strong mass loss in the non conservative evolution of interacting binaries (de Mink et al. 2009), mass loss from very massive stars (Vink 2023), and any of these explanations may aptly describe the present status of the gas in these galaxies, especially in the very young Sunburst galaxy (Pascale et al. 2023). In all these cases, we should be observing a very short phase in the life of the forming galaxy. It is important to emphasize that a model for the formation of second generation stars in GCs must explain several stringent and more complex chemical constraints such as the Na–O and Mg–Al anticorrelations, lithium abundances, high helium populations, maximum value of the helium, discreteness in the distribution of chemical anomalies, as well as a variety of other minor but important properties (see Gratton et al. 2019 for a comprehensive discussion of all these issues). These constraints are so strong that most of models fail to comply with them, and in fact the supermassive stars model (SMS) had been originally developed mainly to deal with the depletion of ^{24}Mg implied by the Mg–Al anticorrelation (Denissenkov & Herwig 2003; Denissenkov & Hartwick 2014). Although with some limitations (Renzini et al. 2015), the asymptotic giant branch (AGB) model (D'Ercole et al. 2008, 2016; Calura et al. 2019) deals particular well with most of the abundance trends, including (Ventura et al. 2012) the extreme Mg–K anticorrelation found in a few clusters (Cohen & Kirby 2012; Mucciarelli et al. 2015; Carretta 2022) and with the variety and discreteness of multiple populations (D'Antona et al. 2016).

The main aim of this letter is to show that the composition of AGB ejecta, diluted with gas that is characterized by the first-generation composition, is compatible with the high N/O found in the spectrum of GN-z11. Simultaneously, it aims to highlight that the long phase of massive AGB evolution is consistent with the time needed to build up the central accreting black (BH) hole of mass $\gtrsim 10^6\,M_{\odot}$ apparently hosted in the system (Maiolino et al. 2023). We remark that the model proposed here represents just a plausible scenario to explain several features of this peculiar object simultaneously, but it is not necessarily the unique solution. The outline of the paper is as follows. We begin by examining the problem of the timescales in Sect. 2. We proceed to compare the abundances in Sect. 3 and we conclude with a discussion of unsolved issues along with possible promising approaches in Sect. 4. In Sect. 5, we compare the timescales for the possible formation route to build the massive BH with the timescale of the AGB evolution. We summarize our results in Sect. 6.

2. Timings involved: Central black hole

If we were witnessing the formation of a second generation, the main difference between the AGB model and all the others is the timescale on which it operates. This event would be ranging from less than a million years, if the source of nitrogen rich gas are SMS (Charbonnel et al. 2023), up to as long as 10 Myr, if the polluters are massive binary interactive stars possibly operating in a "quiet" epoch, when masses of $\gtrsim 25\,M_{\odot}$ evolve directly to black holes, as recently suggested by Renzini (2023). Instead, the massive AGB evolution timescale is on the order of several tens of million years, which is a good reason to raise criticism with respect to their possible role. Senchyna et al. (2023) noted that the timescale of 40 to more than 100 Myr of the AGB evolution is difficult to accomodate into the ∼20 Myr age of the burst we are looking at. According to the analysis of the JADES NIRcam imaging (Tacchella et al. 2023), half of the star formation in central regions has taken place in the last few million years, while an extended star formation epoch at a much smaller rate may have occurred both in the central point and in the extended source. Also, Cameron et al. (2023) discarded the model by noting that a fine tuning is required between the nitrogen production and the lack of oxygen increase associated with the SN II ejecta of the intense star formation at 20 $M_\odot$ yr^{-1}. Basically, such a star formation rate (SFR) leaves scarce space for the long operation of the AGB model, as a very massive second generation would be formed in much less than a million years.

On the other hand, the models these results are based on have not included the possibility that the central regions host an active galactic nucleus (AGN). As pointed out by Maiolino et al. (2023), the observation in the spectrum of high ionization semi-forbidden nebular lines typical of the broad line region of AGNs, as well as of blueshifted lines testifying to the presence of fast outflows, provides a strong indication of the presence of a central accreting black hole (BH). The quantification of the intense star formation should take this into account. Recently D'Silva et al. (2023) revised the star formation history of galaxies including in the fit an AGN component. They found star formation histories that are a factor ∼9 lower than the fit – not including the AGN for galaxies in the range of $z > 9$ – and a reduction even up to 4 dex for individual cases. Thus, the presence of an AGN component in GN-z11 allows us to reconsider both the determination of a total mass of $\sim 10^9\,M_\odot$, and of the SFR of $\sim 20\,M_\odot$ yr^{-1} and take a different approach to the possible timescale where N-rich sources are active.

We have taken on the point of view that the PS component is due to an AGN, while the extended component would be the host galaxy (Tacchella et al. 2023). Scaling of the AGN properties to the case of GN-z11 provides a mass of $\sim 10^6\,M_\odot$ for the central BH (Maiolino et al. 2023), so that GN-z11 also poses an important age constraint on the formation of massive BHs (see Greene et al. 2020, for a general reference). Such a massive BH could be the result of direct collapse of a gas cloud into BH (see, e.g., Latif & Ferrara 2016, and references therein). Otherwise, it must result from mass accretion on typical (20–40 $M_\odot$)[1] stellar remnant BHs or more massive seed BHs runaway stellar mergers (see e.g., Portegies Zwart & McMillan 2002). A favorable environment for the latter scenario is met if we are indeed in the central region of a massive first generation GC. Many BHs would be the remnants of the evolution of the masses $M > 25\,M_\odot$, and repeated stellar BHs early mergers may increase the coalesced BH mass to $\sim 100\,M_\odot$, or even to $\sim 10^3\,M_\odot$ for the largest initial masses of the cluster (Rodriguez et al. 2019; Antonini et al. 2019; Kritos et al. 2023). A BH mass of $\sim 10^6\,M_\odot$ would eventually be reached if there is time for a "long" phase of accretion. Maiolino et al. (2023) estimate 30–150 Myr for this phase, starting from a mass of 100 $M_\odot$, at the super-Eddington mass accretion rates 5 ± 2 times the Eddington rate implied by the AGN luminosity of 10^{45} erg s^{-1}. We note that the presence of an accreting intermediate mass BH, atypical for standard GCs, makes GN-z11 more similar to the nuclear star clusters (NSC) at the center of galaxies (Ferrarese et al. 2006; Neumayer et al. 2020). If we are at the centre of a massive cluster, the time lapse for the accretion phase may be met during the long period of quiet following the Supernovae type II (SN II) epoch, during which the massive AGB winds accumulate in a central cooling flow and form the second generation stars, as envisioned by the AGB model (D'Ercole et al. 2008, 2016) and now supported by 3D hydrodynamical simulations (Calura et al. 2019; Yaghoobi et al. 2022). The growth of a central BH to masses up to $\sim 10^4\,M_\odot$ had been modeled in this context by Vesperini et al. (2010), considering only sub–Eddington or Eddington accretion rates on a relative low–mass seed BH ($\sim 100\,M_\odot$) possibly produced by early stellar mergers. If super-Eddington rates are allowed, the mass at $z = 10.6$ may indeed become as large as $\sim 10^6\,M_\odot$, as required. Still, we note that the cooling flow of the AGB model does not require the presence of a central BH, as it is due to the gravitational well of the first-generation cluster. The AGB model for the formation of the second generation in GCs then provides a favorable set for the build-up of the central BH, unlike other possible models, which must rely on the hypothesis of a BH massive from its birth.

3. Comparison of abundances

It is necessary to examine whether the chemistry of the AGB ejecta can reproduce the observed N/O and C/O abundances of the emission spectrum. In Fig. 1, we plot the error boxes (Cameron et al. 2023) of GN-z11 in the log(N/O) and log (C/O) versus 12+log(O/H) planes. The results for N/O and O/H of the analysis made by examining detailed nebular models (Senchyna et al. 2023) are reported as an open black square. The coloured squares in the plots represent the average abundances of the ejecta from the AGB models of different mass and metallicity, as listed in the figure (Ventura et al. 2013). The abundances in the starting main sequence models are represented by the asterisks and we see that they are typical abundances consistent with the values found for the compact local galaxies (Izotov et al. 2012). The black lines drawn between the AGB ejecta and the initial composition represent examples of the possible dilution of the AGB gas and gas with the primordial composition of the interstellar medium. Considering different degrees of dilution, we can fit the abundances within the fiducial and/or conservative error box, after excluding the lowest metallicity models ($Z = 0.0002$, or initial log(O/H)+12 = 7.68) clearly out of the errors. The highest metallicity ($Z = 0.004$ or initial log(O/H)+12 = 8.04) is well within the fiducial error box with the ejecta of the 5 $M_\odot$. The two intermediate metallicity evolutions ($Z = 0.001$ and $Z = 0.002$) are both compatible with the composition of gas in GN-z11, for a variety of possible dilution with gas having the initial metallicity of the first generation. In Table 1 we provide an estimate of the dilution required to obtain an abundance within the fiducial or the conservative error box.

4. Considering whether GN-z11 could be a "typical" second generation formation stage

When we consider the role of AGB ejecta and the dilution with gas having the composition of the first-generation stars, we question whether we are implicitly assuming to be dealing with the formation in a typical GC? The presence of a massive BH with a mass $\sim 10^6\,M_\odot$ is a clear indication that that is not the case and that the system investigated is instead likely to be the progenitor of a NSC. In the rest of this section we discuss other aspects that may differentiate the evolution of a typical GC from that of the GN-z11 massive star cluster.

If the SN II ejecta of the first generation were expelled out of the system, we ask whether the second generation may form

[1] We adopt here the BH masses from the models by Limongi & Chieffi (2018) for [Fe/H] = −1, in the mass range 25–80 $M_\odot$.

Table 1. Age of the Universe (Col. 6) at the time of formation of the system progenitor of GN-z11 if $M_{\rm AGB}$ (Col. 2) is polluting the medium at age 430 Myr.

Z	$M_{\rm AGB}$ $M_\odot$	Dilution % Fiducial	Dilution % Conservative	AGB age (Myr)	Age (Myr)
0.001	7.5	X	0–40	46.2	384
	7.0	X	10–60	52.5	378
	6.0	X	60–80	70.8	360
	5.0	X	30–60	102	330
	4.0	X	10–30	168	262
0.002	7.0	60–80	0–60	51.4	379
	6.0	60–80	0–60	69.8	360
	5.0	40–60	0–60	100	330
	4.0	60	60	167	263
0.004	6.0	X	0–20	70.1	360
	5.0	0–10	0–10	102	328
	4.0	X	X	169	261

without contamination from the supernova ejecta of the first generation. In the original AGB model by D'Ercole et al. (2016), it was proposed that the central bubble powered by the SN II breaks out of the disk of the host (dwarf) galaxy forming a funnel through which the ejecta are lost. But if we apply the model to the physical conditions in GN-z11 central regions (derived from the spectral energy distribution by models not considering the AGN component emission), the stalling radius[2] (where the velocity expansion equals the sound speed of the surrounding ISM and the bubble stops its growth) may become too small and the ejecta remain in the cluster if the densities are larger than $\sim$100 cm^{-3} (the lower range of the values given by Bunker et al. 2023). The model is fully excluded if the densities were $n \simeq 10^5$ cm^{-3} (Senchyna et al. 2023) because the stalling radius would be only 17 pc, but also because the PS volume would contain more than $20 \times 10^6\,M_\odot$ and such a value seems too high for a second generation made up by AGB ejecta. It is important to keep in mind that the density values derived so far do not consider the AGN. If the massive cluster in GN-z11 is a NSC, the possible metallicity variations produced as a result of the retention of SN ejecta are not a problem.

We go on to consider whether standard "dilution" might be feasible. In spite of the presence of a central AGN emission, we maintain the idea that a first generation cluster is also present: it is needed both to produce the initial BH seeds and a favorable environment for their merging, and to obtain a cooling flow and star formation in a concentrated region. Observationally, most galactic GCs can still be considered mono-metallic, since the upper limit to the scatter of iron is less than $\sim$0.05 dex (Carretta et al. 2009). It is only recently that a somewhat larger spread has been isolated in the first-generation stars of some GCs (Legnardi et al. 2022), but the strict homogeneity of the second generation stars (in spite of the variations in p-capture elements abundances) has been confirmed. This latter result points to a homogeneous mixing of the gas producing the second generation stars, probably due to its formation in a very compact region, such as the cooling flow, which is an indirect confirmation of the AGB model.

In the case of GN-z11 the chemical evolution and dynamics can be considerably different. In particular, we are at such a young age that the Universe is recently emerging from the dark epoch, so the proto–galaxy or proto–cluster is probably still surrounded by dense neutral gas, which may take part in the accretion process. Further, AGB ejecta may be accreting from a larger region than the first generation cluster, and the ongoing event of star formation may produce also exploding and polluting core collapse supernovae. At the same time, the surrounding gas probably has a metallicity that is lower than the pristine gas of the first-generation stars and its accretion may counteract the overall medium metallicity increase due to the recent supernovae (see, e.g., Heintz et al. 2023). If instead the gas composition is more metallic due to supernovae, it is possible that the first generation was less metallic than assumed in the simple dilution, putting the models at $Z = 0.0002$ that we had dismissed back into play. Metallicity variations in large fractions of the stars are present in a few galactic GCs, such as ω Cen, which are in fact often regarded as remnants of NSCs, as GN-z11 could be. In summary, the dilution with gas having the "same composition of the first generation stars", as shown in Fig. 1, is probably an oversimplified view; however, with respect to the present context, since most of the ejecta compositions are considerably N-rich, any more complex dilution of the ejecta will be generally compatible with the GN-z11 spectrum, albeit possibly requiring a bit different initial composition to the first generation stars.

Finally, we consider whether the accretion going on onto the central BH modifies the process of star formation. Accretion on the central BH puts another difference between the "standard" AGB model and the present case. The AGN injects energy into the surroundings through the process of accretion-driven feedback, enhancing the velocity dispersion of the gas in the cooling flow and/or driving the fast gas outflows actually seen in the spectrum (Maiolino et al. 2023). The problem is discussed in Vesperini et al. (2010). It is possible that accretion is intermittent, and that star formation is active mainly during the quiescent phases of the BH. On the other hand, intermittency lengthens the time required to accumulate a BH mass of $10^6\,M_\odot$ (Milosavljević et al. 2009). One point to notice is that in this NSC environment, a favorable circumstance is that the AGB ejecta may be accreting from a larger region than the first generation cluster, as the high N/O is similar for several stellar masses and a strict coevality is not necessary for the polluting AGB gas to show the N/O observed in GN-z11.

In conclusion, while we are far from a conclusive "model" for the possible formation of a second generation population in GN-z11, the main point now is that we are witnessing the role of massive AGB winds in polluting a medium where a massive globular cluster is present, even if the final system that emerges will be more complex than a standard GC.

5. Examples of the timing to the present stage of GN-z11

Contrary to previous discussions in the literature, here we claim that the main point of advantage in identifying as massive AGB the polluters of the gas in GN-z11 is the relatively long timescale

[2] Albeit a little inappropriately, bubbles whose radiative losses are negligible in front of the mechanical luminosity L_w of the SN wind are called "energy conserving"; in the opposite case the bubble shell is directly driven by the wind pressure and is called "momentum conserving". For the energy conserving and momentum conserving bubbles the stalling radii are given, respectively, by $R_{\rm st,e} = 48\left(\frac{L_{36}}{n}\right)^{0.5}$ pc and $R_{\rm st,m} = 5\left(\frac{L_{36}}{n}\right)^{0.5}$ pc, where the mechanical luminosity of the wind is given in units of 10^{36} erg s^{-1} and n is the numerical density of the ISM in cm^{-3}, see D'Ercole (1992) and references therein, but note that here the numerical coefficients are a bit lower because we do not consider the contribution of stars more massive than 25 $M_\odot$.

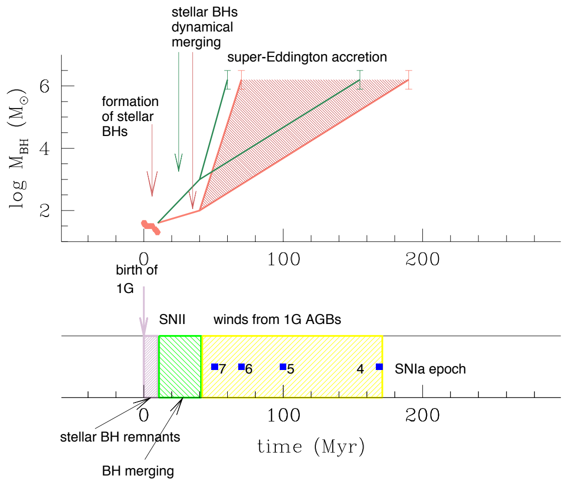

Fig. 2. Sketch of the players in the game. At the bottom, we show the "ruler" of timescales in a standard Globular Cluster in the AGB model and at the top we show the possible growth of the central BH. The time origin is set at birth of the first generation (1G). Grey box: Formation of BHs of 40–20 $M_{\odot}$ from the evolution of the most massive stars down to ∼25 $M_{\odot}$ (∼10 Myr); green box: SN II epoch, scarce presence of gas; stellar BHs merge and leave a seed BH of 100–1000 $M_{\odot}$ (red and green lines in the upper panel; ∼30 Myr). Yellow box: "Quiet" period of AGB evolution, the evolving masses are marked as blue squares. AGB ejecta and the re-accreting interstellar gas mix and produce the cooling flow giving origin to the formation of the second generation. Part the gas collecting into the central regions also feeds the BH (≲130 Myr). Afterwards, SN Ia begin exploding in the cluster. In the upper panel of the figure we show schematically how Super-Eddington accretion allows the BH to reach the mass of $\log(M/M_{\odot}) = 6.2 \pm 0.3$, starting from a BH of 100 $M_{\odot}$ (red triangle) or 1000 $M_{\odot}$ (green lines). Accretion occurs at the rates suggested from the AGN luminosity, following Maiolino et al. (2023).

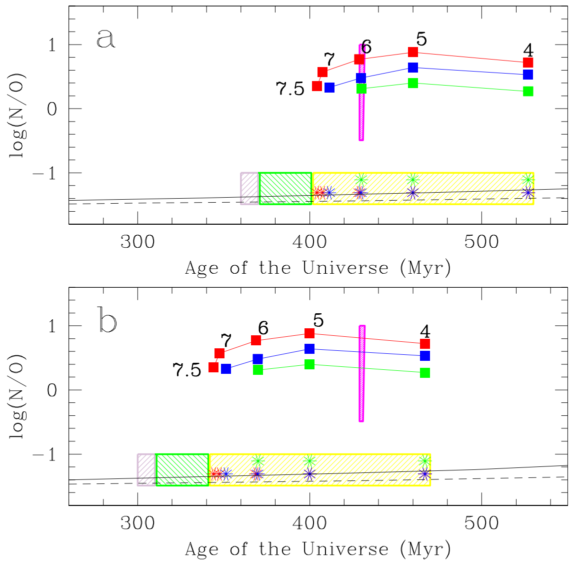

Fig. 3. Two possible examples of the evolution in the proto–nuclear star cluster GN-z11, in the hypothesis that the AGB winds mixed with standard interstellar gas constitute the gas responsible for the high (N/O) abundances in the spectrum. The intra cluster medium exhibits the correct N/O, when polluted by the ejecta properly diluted of any of the intermediate mass AGB stars. The pink rectangle is the fiducial error box by Cameron et al. (2023) for GN-z11. In panel a, we assume that the 6 $M_{\odot}$ is the mass presently evolving, while in panel b we assume that the 4.5 $M_{\odot}$ is evolving, at the age of 430 Myr. The formation of the 1G is shifted back by 70 Myr (the evolution age of the 6 $M_{\odot}$) in panel a and by 130 Myr (the evolution age of the 4.5 $M_{\odot}$), respectively at ∼360 Myr or ∼300 Myr, as shown by the "ruler" drawn at the bottom. Asterisks denote the initial log(N/O) in the models, and colored squares represent the abundance in the ejecta. If we were to be witnessing the evolution of a larger (smaller) mass, the AGB abundances and the boxes would be all shifted to larger (smaller) age. The two lines at the bottom represent the time evolution of log(N/O) for the upper (full line) and lower (dashed) envelope of the chemical evolution models by Vincenzo et al. (2016).

tracing their activity. In Fig. 2 we sketch the "ruler" of the interval of time between the formation of a first generation of stars and the end of the massive AGB phase.

During the first 10 Myr, the most massive stars down to ∼25 $M_{\odot}$ end their life into black hole remnants (possibly without exploding as SN), shown in the grey box. For all other models invoking the second-generation star formation, the timeline of the event must be confined within the first 2–3 Myr or (at most) within the 10 Myr window indicated by the grey box. After that, the explosions of SN II goes on for a long period (∼30 Myr), during which star formation is either totally suppressed because most of the gas is expelled out of the cluster or it proceeds at a slower pace, while the dynamical interactions of the just formed remnant BHs in the central region lead to merging events beginning to increase the seed BHs. When the stars begin evolving into white dwarfs and the SN II epoch ends, the interstellar gas and the N/O rich AGB ejecta begin falling back to the GC core, with the double effect of accreting gas on the central BH and of forming the second generation stars. Sequentially, smaller masses evolve over time. Here, we limit the time span to the evolution of the 4 $M_{\odot}$ at ∼170 Myr, that is to say, fully including the extreme period in which s–Fe–anomalous clusters are formed (D'Antona et al. 2016).

Practically all the intermediate mass AGB stars (especially for $Z = 0.002$) may pollute the intra cluster medium and provide the observed (N/O), but there is no way to know which mass is contributing in the moment, at the age of 430 Myr. The formation of the pristine GC will go back in the past by 50 Myr (if now the ∼7 $M_{\odot}$ is evolving) to 170 Myr (if the 4 $M_{\odot}$ is presently evolving) and the formation of the first generation is pushed back to $z \simeq$ 15–12 and ages of the Universe of only 260–380 Myr (Col. 6 in Table 1), fully into the pre–reionization epoch, leaving enough space for the first galaxies to have already formed (Robertson 2022; Harikane et al. 2022; Calura et al. 2022). Positioning our ruler by imposing that a particular mass is evolving now in GN-z11 at the Universe age of 430 Myr, we visualize the age of formation of the first generation and the timespan for accreting the central BH in GN-z11. Two examples are shown in the panels of Fig. 3, based on the hypothesis that the AGB ejecta of the 6 $M_{\odot}$ (or 4.5 $M_{\odot}$) are in the accreting gas responsible for the high (N/O) abundances in the spectrum. The 6 $M_{\odot}$ (4.5 $M_{\odot}$) takes ∼70 Myr (∼130 Myr) to evolve, so the first generation stars were born at ∼360 Myr (∼300 Myr). After 40 Myr the accretion phase begins. Confronting the available times with the upper panel in Fig. 2, we see that in both cases, the BH may reach the value of the BH in GN-z11 if subject to super-Eddington accretion.

6. Conclusions

We examine the possibility that the high N/O in the spectrum of GN-z11 is due to the presence of CNO cycled gas forming a second generation in a massive globular cluster. Our conclusions are:

1. GN-z11 morphology, points either to a very concentrated star formation event and/or to AGN emission in matter enriched by N/O rich ejecta;
2. We have shown that the ejecta of massive AGB of a first-generation globular cluster, mixed with the interstellar matter, provide values of N/O consistent with the abundances in the spectrum of GN-z11. The scenario is probably more complex than in a standard GC second generation formation: as the emission of the central point of GN-z11 is probably due to an AGN type emission, from a BH mass of $\sim 10^6\,M_\odot$ (Maiolino et al. 2023), the cluster resembles more so a nuclear star cluster than a standard GC;
3. The models of formation of the second generation proposed thus far are active for a time span of ∼1 Myr to ∼10 Myr. The time span of activity of the AGB model is much longer, extending up to 130 Myr;
4. The presence of a first generation cluster that has formed many stellar BH as remnants in the first few Myr of life is critical to produce a central seed BH with mass of ∼100–1000 $M_\odot$, through mergers in the system dense central environment;
5. the long duration of the massive AGB phase of pollution and of the associated cooling flow is a favorable environment for accreting the BH mass to the high value proposed for GN-z11 BH, at an age of the Universe that is as young as 430 Myr, without having to resort to the hypothesis of a direct collapse leading to the rapid formation of such a massive BH.

In summary, we propose a scenario to explain a few fundamental properties of the GN-z11 system observed at $z = 10.6$ by JWST. Our study shows that the observed properties of this system are consistent with a model combining the formation of second generation stars with large N/O out of pristine gas and AGB ejecta and the growth of a massive BH from gas accretion on a central seed BH. Star formation and the growth of super massive BHs are key ingredients in galaxy formation and in future studies it will be fundamental to understand the role of each component in defining the spectrum of GN-z11 and other similar systems at high redshift.

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