

# XMP gas-rich dwarfs in nearby voids: candidate selection

S. A. Pustilnik<sup>1</sup>, E. S. Egorova<sup>2</sup>, Y. A. Perepelitsyna<sup>1</sup> and A. Y. Kniazev<sup>2,3,4</sup>

<sup>1</sup>Special Astrophysical Observatory of RAS, Nizhnij Arkhyz, Karachai-Circassia 369167, Russia

<sup>2</sup>Sternberg Astronomical Institute of Moscow State University, Moscow, 119992, Russia

<sup>3</sup>South Africa Astronomical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa

<sup>4</sup>South African Large Telescope, PO Box 9, 7935 Cape Town, South Africa

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## ABSTRACT

We introduce a project aimed at systematically searching for eXtremely Metal-Poor (XMP) very gas-rich blue dwarfs in voids in the nearby Universe. Several such galaxies were first identified in the course of an unbiased study of the galaxy population in the nearby Lynx-Cancer void. These very rare and unusual galaxies appear to be the best proxies for the so-called Very Young Galaxies defined recently in the model simulations by Tweed et al. (2018). We discuss the main properties of 10 prototype objects residing in nearby voids and formulate criteria to search for similar dwarfs in other voids. The recently published sample of 1354 Nearby Void Galaxies is used to identify a subsample of 60 void dwarf XMP candidates. We provide a list of these XMP candidates with their main parameters and finding charts. These candidates are the subjects of subsequent spectral, photometric, and HI studies in the accompanying papers. Looking ahead, with reference to the submitted accompanying papers, we find that this study results in the discovery of many new XMP dwarfs with  $12+\log(\text{O}/\text{H}) \sim 7.0\text{--}7.3$  dex.

**Key words:** galaxies: abundances – galaxies: dwarf – galaxies: evolution – galaxies: photometry – large-scale structure of Universe.

## 1 INTRODUCTION

Since the discovery about a half century ago of the unusual Blue Compact Dwarf Galaxy (BCDG) with extremely low gas metallicity, IZw18 (=MRK 116) [ $Z_{\text{gas}} \sim Z_{\odot}/30$ ; Searle & Sargent 1972], interest in these rare galaxies has suffered ups and downs. One of the motivations to search for other similar BCDGs was a hope that such unusual dwarfs could be used as proxies for primordial galaxies at high redshifts (see e.g. the review by Kunth & Östlin 2000). Such objects are also the best probes of an important cosmological parameter – the abundance of primordial Helium (e.g. Izotov, Thuan & Lipovetsky 1997; Aver, Olive & Skillman 2012).

Recent interest in such objects is caused by the results of massive spectroscopic surveys of faint galaxies mostly found in the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009; Abolfathi et al. 2018; and references therein). Several groups used this data base to search for eXtremely Metal-Poor (XMP) candidates and investigated them with high-quality follow-up spectroscopy (e.g. Kniazev et al. 2003; Izotov et al. 2006; Izotov & Thuan 2007; Izotov et al. 2012, 2016; Sanchez Almeida et al. 2016; Guseva et al. 2017).

Despite having spectral data for more than one million galaxies, due to various observational selection effects and the survey limits, gas metallicity at the level of  $Z \lesssim Z_{\odot}/10$ , or  $12+\log(\text{O}/\text{H})$

$\lesssim 7.69$  dex, was only found in a few hundred galaxies (Izotov et al. 2016, 2019b). To date, a dozen or fewer XMP galaxies have a reliable value of  $Z_{\text{gas}} \lesssim Z_{\odot}/30$  (see Izotov et al. 2019b, based on SDSS DR14 data base).

Meanwhile, other means were also used to search for such rare objects during the last decade. The first one exploits the correlation of very low gas metallicity with low galaxy luminosity and with elevated gas content. A high-sensitivity blind HI survey with the Arecibo radio telescope (ALFALFA; Haynes et al. 2018) over an area of  $\sim 7000$  square degrees resulted in  $\sim 35\,000$  confident extragalactic HI-bearing objects with radial velocities up to  $\sim 16\,000$  km s<sup>−1</sup>. A substantial number of them appear to be rather close low-mass dwarfs with previously unknown radial velocities, mostly due to the bias of the main optical redshift surveys.

The dedicated project, SHIELD (Cannon et al. 2011; McQuinn et al. 2014; Hauberg et al. 2015), aimed to study a subsample of faint gas-rich ALFALFA dwarfs, and found several interesting dwarfs, including the record-low object AGC198691 with  $12+\log(\text{O}/\text{H}) = 7.02$  (Hirschauer et al. 2016) at distance  $\sim 11$  Mpc. One more XMP dwarf, Leo P, with  $12+\log(\text{O}/\text{H}) = 7.17$ , was found close to the Local Group ( $D = 1.65$  Mpc; Skillman et al. 2013).

An ‘almost’ dark very LSB dwarf, Coma P = AGC229386 at  $D = 5.5$  Mpc, with a record high ratio  $\text{MH}/L_{\text{B}} = 28$  (Janowiecki et al. 2015; Brunker et al. 2019), could also fall into the same category of objects. However, its estimated metallicity of stars of  $Z = 0.002$  (Brunker et al. 2019) that corresponds to

\* E-mail: sap@sao.ru

$12+\log(\text{O}/\text{H}) = 7.8$ , appears too high. So, it is difficult to assign this gas-rich dwarf to the XMP category.

For this kind of candidate selection, the overall detection rate for new XMP galaxies appears higher than for SDSS emission-line galaxies. However, the total number of XMP dwarfs found this way still remains very small.

New selection methods of XMP candidates based on galaxy photometric properties as extracted from the SDSS data base have been suggested. First, galaxies have been examined within the parametric space (colours, morphology, sizes) typical of Leo P and similar XMP galaxies found among galaxies with the SDSS images. In particular, James et al. (2017) found 11 dwarfs with  $Z \lesssim Z_{\odot}/10$  among 50 blue diffuse dwarf (BDD) candidates. However, the lowest values of O/H are not extremely low and all have  $12+\log(\text{O}/\text{H}) > 7.4$  dex.

A similar method was used by Hsyu et al. (2017, 2018). For their selected candidate sample of  $\sim 150$  blue late-type galaxies, they found with follow-up spectroscopy one good nearby XMP object (dubbed as ‘Little Cub’) with  $12+\log(\text{O}/\text{H}) = 7.13$ , while all their other candidates have  $12+\log(\text{O}/\text{H}) > 7.4$  dex. Thus, summarizing, we conclude that due to various observational selection effects, the search for new XMP galaxies is very difficult. Due to the well-established statistical relation between metallicity and luminosity, one expects that the great majority of late-type galaxies with  $M_{\text{B,tot}} > -13$  should have  $Z_{\text{gas}} \lesssim Z_{\odot}/10$ . However, in reality such galaxies appear substantially more rare (Sanchez Almeida et al. 2017).

Finally, we have suggested one more method for finding XMP dwarfs (Pustilnik & Tepliakova 2011; Pustilnik, Perepelitsyna & Kniazev 2016). It is based on the confident finding of an overall metallicity deficiency (on average, by a factor of  $\sim 1.5$ ) of late-type galaxies in voids with respect to similar objects in denser environments (typical groups) (Pustilnik, Perepelitsyna & Kniazev 2016; Kniazev, Egorova & Pustilnik 2018). Moreover, it was found that  $\sim 1/3$  of about 20 of the faintest Lynx-Cancer void late-type dwarfs show reduced gas O/H by a factor of 2–4 with respect to a control sample of similar galaxies in denser environments (Perepelitsyna, Pustilnik & Kniazev 2014; Pustilnik, Perepelitsyna & Kniazev 2016). The same objects have the extremely high gas mass fraction of 0.95–0.99 and show blue colours in their outer regions.

If we extrapolate this finding based on rather small statistics to late-type dwarfs in other nearby voids [so-called Nearby Void Galaxies (NVG) sample, see Section 2], we can expect roughly  $1/3$  of all  $\sim 180$  NVG objects with  $M_{\text{B,tot}} > -13$  to have  $Z_{\text{gas}} \lesssim (Z_{\odot}/30 - Z_{\odot}/20)$ . While this is quite a strong prediction, to check this, one needs good statistics, and hence, high-quality spectroscopy of a major fraction of known intrinsically faint NVG objects.

The important question regarding the minimal metallicity of gas in galaxies in the nearby Universe is related to the history of intergalactic medium (IGM) enrichment. According to various indications, outside the sites of significant galaxy concentration (massive galaxy groups and clusters), the local IGM is considered largely to have a metallicity of 1–2 per cent of the solar value. The so-called cold accretion of this gas to low-mass dark matters haloes is considered as one of the main processes of dwarf galaxy build-up. If the gas that forms stars in galaxies has been partly accreted from the IGM through cold-flows, then the IGM metallicity sets a lower limit for the metallicity in XMPs (e.g. Sanchez Almeida et al. 2014, and references therein). It is worth mentioning that in the distant Universe, at redshifts of  $z \sim 3.1$  and  $\sim 4.4$ , clear evidence is found for much lower metallicity in the IGM of  $\sim 0.001$  and even  $\sim 0.0001$  the solar value (Cooke et al. 2017; Robert et al. 2019).

For the local Universe galaxies, metallicity of  $\sim 0.02 Z_{\odot}$  (or  $12+\log(\text{O}/\text{H}) \sim 7.0$  dex) has been found for only a handful of objects. Two of them, found recently by Izotov et al. (2018, 2019a), are actively star-forming dwarfs (or blue compact dwarfs), at distances of  $\sim 186$  and  $650$  Mpc, respectively. As shown by Izotov et al. (2018) with the comprehensive SED fitting, in J0811+4730, the mass of the stellar population with ages of 1–10 Gyr is smaller (or much smaller) than the mass of the young population.

One of the caveats of their analysis is related to the small diameter of used spectrograph fibres,  $\sim 3$  arcsec corresponding to the linear diameter of  $\sim 3$  kpc at the galaxy distance. One cannot exclude the possibility that outside the region of the current starburst, which contributes the major part of the light in the SDSS spectrum of this BCG, there exists a disc of old stars with a mass comparable to or larger than the mass of the ‘young’ population. With this reservation, these distant XMP dwarfs can be treated as probable counterparts of the predicted Very Young Galaxies (VYGs) that formed the majority of their stars during the last one or so Gyr (Tweed et al. 2018).

Moreover, as shown in the comprehensive analysis of all available data for the prototype XMP blue compact galaxy IZw18 and its fainter companion IZw18C by Papaderos & Östlin (2012), despite the detection with *HST* of red giant branch stars, the conclusion that the main stellar mass was formed during the very recent cosmological epoch ( $\sim 1$  Gyr) remains valid. The reddish light at the periphery of the main star-forming regions is dominated by the strong nebular emission of the ionized gas. The presence of this highly inhomogeneous nebular emission in peripheral regions complicates background subtraction and may affect the analysis of the *HST* colour–magnitude diagram of stars in these regions. For IZw18C, the analysis of all available data leads to ages of stellar populations of  $\lesssim 0.1$  Gyr. Of course, one cannot exclude the presence of faint emission of populations with cosmological age, but their possible mass is lower than the mass of the visible components. That is, in this context, IZw18 and IZw18C also should be treated as the best proxies for VYGs.

We mention also the results of the *HST* data analysis for the system of IZw18 and IZw18C by Annibali et al. (2013). They confirm the detection of the substantial stellar population with ages of  $\gtrsim 1$  Gyr. Based on this fact, the authors conclude that IZw18 is not a truly young galaxy forming its first generation of stars. However, we use in this paper the relaxed definition of VYG as suggested by Tweed et al. (2018). Within this framework, with the current limits to their ancient star formation history and the mass of stars with ages of a few to 10 Gyr, IZw18 and IZw18C have properties consistent with their being VYGs.

The simulated VYGs appear both as central galaxies in the low-mass dark matter haloes and as their satellites. In the lowest mass range,  $M_{*} \lesssim 10^7 M_{\odot}$ , the fraction of VYGs among satellites is comparable to or larger than that for central galaxies (Tweed et al. 2018). It is interesting to compare this with current observational results. In particular, Sanchez Almeida et al. (2017) in their observational study of very low metallicity dwarfs conclude that they are the central galaxies. On the other hand, among the known prototype XMP dwarfs in Table 1 there are several fainter members of pairs or triplets.

A few dwarfs with similar extremely low gas O/H [ $12+\log(\text{O}/\text{H}) \lesssim 7.0$ – $7.1$ ], but with much lower star formation rate (SFR), were found in the nearby Lynx-Cancer void at distances of 10–25 Mpc (Hirschauer et al. 2016; Pustilnik et al. 2016). The majority of them also show blue colours in their outer parts, consistent with a time since the onset of the main star formation (SF)

**Table 1.** Parameters of known prototype void very gas-rich XMP dwarfs.

| IAU name   | O/H<br>(dex)            | $\frac{MH}{L_B}$ | $\mu_{B,0,c}$ | $M_B$<br>(mag) | $(g-r)_0$<br>(mag) | $V_h$ | $D$<br>(Mpc) | logMH | log $M_*$ | $B_{tot}$<br>(mag) | Notes                        |
|------------|-------------------------|------------------|---------------|----------------|--------------------|-------|--------------|-------|-----------|--------------------|------------------------------|
| 1          | 2                       | 3                | 4             | 5              | 6                  | 7     | 8            | 9     | 10        | 11                 | 12                           |
| J0015+0104 | 7.03 ± .05 <sup>a</sup> | 2.4              | 24.5          | −14.07         | 0.19               | 2031  | 28.4         | 8.32  | 6.68      | 18.31              | in Eridanus void             |
| J0113+0052 | 7.16 ± .05              | 4.2              | —             | −14.20         | —                  | 1175  | 16.2         | 8.52  | —         | 16.90              | UGC772, merg.                |
| J0706+3020 | 7.06 ± .05 <sup>a</sup> | 17.1             | 25:           | −12.47         | −0.08              | 952   | 16.9         | 8.41  | 6.2:      | 19.15              | in merg. tripl. UGC3672      |
| J0926+3343 | 7.12 ± .03              | 3.2              | 25.4          | −12.90         | 0.09               | 536   | 10.6         | 7.86  | 6.11      | 17.34              |                              |
| J0929+2502 | 7.10 ± .08 <sup>a</sup> | 2.4              | 24.1          | −12.95         | 0.16               | 1661  | 25.7         | 7.75  | 6.54      | 19.24              |                              |
| J0943+3326 | 7.02 ± .02              | 6.5              | —             | −10.47         | 0.05               | 514   | 11.0         | 7.19  | 5.46      | 19.82              | AGC198691, pair with UGC5186 |
| J0956+2850 | 6.96–7.15               | 3.0              | —             | −13.9:         | 0.05               | 502   | 12.7         | 8.22: | 6.6:      | 16.7:              | DDO68B, in merg. tripl.      |
| J2104−0035 | 7.07 ± .07              | 4.1              | —             | −13.20         | −0.04              | 1395  | 17.2         | 8.29  | 6.0:      | 18.07              | PGC1139658, merg.?           |
| J0723+3622 | —                       | 11.9             | 24.4          | −11.76         | −0.01              | 970   | 16.0         | 7.98  | 5.90      | 19.46              | in tripl. J0723+36           |
| J0723+3624 | —                       | 28.3             | 24.6          | −9.56          | 0.08               | 938   | 16.0         | 7.46  | 5.00      | 21.68              | in tripl. J0723+36           |
| J0811+4730 | 6.98 ± .02              | —                | —             | −15.07g        | —                  | 13323 | 182          | —     | 6.24      | 21.37g             | Izotov et al. (2018)         |
| J1234+3901 | 7.03 ± .03              | —                | —             | −17.32g        | —                  | 39863 | 546          | —     | 7.13      | 21.92g             | Izotov et al. (2019a)        |

*Notes.* Full description of columns is given in Section 3. We briefly recall their meaning. Column 2: gas O/H in units  $12+\log(O/H)$ ; Column 3:  $MH/L_B$  in solar units; Column 4: corrected central surface brightness  $\mu_{B,0,c}$  in  $\text{mag}/\square''$ ; Column 5: absolute  $B$ -band magnitude. Superscript  $g$  for the two distant XMPs relates to SDSS  $g$  band. Column 6: corrected for MW extinction total  $g-r$  colour; Column 7: heliocentric radial velocity in  $\text{km s}^{-1}$ ; Column 8: adopted distance in Mpc; Column 9: log of galaxy HI-mass in  $M_\odot$ ; Column 10: log of stellar mass in  $M_\odot$ ; Column 11: total  $B$ -band magnitude; and Column 12: notes. We abbreviate triplet as tripl. (see Section 5.1 for detail) and merger/merging as merg. Low accuracy data are marked with (:).

<sup>a</sup>O/H derived via the strong-line method by Izotov et al. (2019b) −0.03 dex to match off-set from  $(O/H)_{Te}$ .

episode of  $\lesssim 1\text{--}3$  Gyr as well as the extreme gas-mass fractions,  $M_{\text{gas}}/M_{\text{bary}} \sim 0.96\text{--}0.99$ . However, due to their low luminosity and faint emission lines, they are usually bypassed by typical redshift surveys.

After the discovery of the unusual void dwarfs that appeared to be almost exclusively the least luminous blue LSB galaxies in the Lynx-Cancer void, it is tempting to look for similar objects in other nearby voids. This is now possible thanks to the recently published ‘NVG’ sample (Pustilnik, Tepliakova & Makarov 2019, hereafter **PTM19**; see Section 2 for details). We use this sample to separate a group of about 60 NVG low-luminosity late-type dwarfs as candidate gas-rich XMP galaxies for follow-up spectroscopy with the SAO Big Telescope Alt-azimuth (BTA; 6-m telescope; Ioannisianni et al. 1982) and Southern African Large Telescope (SALT; Buckley, Swart & Meiring 2006; O’Donoghue et al. 2006) to determine their gas O/H. Besides the follow-up spectroscopy, additional studies include optical photometry and HI mapping. All results of this study will be presented in a series of accompanying papers, either submitted or in preparation.

The rest of this paper is arranged as follows. In Section 2, we briefly summarize the Nearby Void Galaxies sample. In Section 3, we describe the small group of prototype XMP void dwarfs and their main properties. Section 4 presents the criteria that we applied to separate out the subsample of candidate void XMP dwarfs together with the resulting list. In Section 5, we discuss the issues of XMP dwarfs and VYGs. Finally, in Section 6 we summarize and present our conclusions.

## 2 NEARBY VOID GALAXIES SAMPLE

The ‘Nearby Void Galaxies’ catalogue is a collection of galaxies that fall inside 25 voids in the volume with  $R = 25$  Mpc (**PTM19**). In total, 1354 galaxies within these voids are catalogued. The galaxies have absolute blue magnitudes  $M_B$  in the range of  $-7.5$  to  $-20.5$ , with the median  $M_{B,\text{med}}$  of  $\sim -15.2$ . Of them, 1088 void galaxies reside in the ‘inner’ parts of void, having a distance to the nearest bordering ‘luminous’ galaxy  $D_{NN} \geq 2.0$  Mpc (with the median

of  $D_{NN,\text{med,inner}} = 3.4$  Mpc). The rest of the NVG sample objects reside in ‘outer’ parts of voids, closer to their borders. Their median parameter  $D_{NN,\text{med,outer}} = 1.6$  Mpc.

About 200 NVG sample objects fall within the Local Volume, i.e. the region within  $R = 11.0$  Mpc. Thanks to their proximity, they are especially promising for more detailed study, including the study of resolved stellar populations with the *HST* and *JWST*.

The main NVG sample is important for several reasons related to the role of environment in galaxy evolution. This is, on the one hand, much deeper than any other void galaxy sample, and, on the other hand, contains hundreds of low-mass/luminosity dwarfs that comprise the great majority of the void galaxy population. This gives us an advantage in comparison to similar studies based on more distant and more shallow void galaxy samples (e.g. Kreckel et al. 2012, 2015; Wegner et al. 2019) to look for the effect of void environments on the most numerous low-mass objects.

## 3 PROTOTYPE UNUSUAL XMP GAS-RICH DWARFS

To increase the efficiency of XMP dwarf searches among the NVG representatives, we need, on the one hand, to better outline the observational peculiarities of already known dwarfs in this group (based mainly on objects from the Lynx-Cancer void). On the other hand, the real range of parametric space of void XMP galaxies could be wider than we know from their small already known subgroup. To account for this fact, we may try to expand somewhat the known ranges.

In Table 1, we summarize the properties of eight currently identified representatives of these unusual XMP dwarfs in the nearby voids and two extremely gas-rich blue void dwarfs with unknown O/H, which very likely belong to the same type. Four of eight XMP gas-rich objects in the upper part of Table 1 (J0706+3020, J0926+3343, J0929+2502 and J0956+2850) were found as a result of an unbiased study of a sample of about 100 galaxies in the nearby Lynx-Cancer void (Pustilnik, Kniazev & Pramskij 2005;

Pustilnik et al. 2010, 2011; Chengalur & Pustilnik 2013; Pustilnik & Martin 2016; Pustilnik, Perepelitsyna & Kniazev 2016; Chengalur, Pustilnik & Egorova 2017). The entry J0956+2850 corresponds to the smaller component of the well-known dwarf merging system DDO68 (Pustilnik, Kniazev & Pramskij 2005; Ekta, Chengalur & Pustilnik 2008; Makarov et al. 2017) for which  $12+\log(\text{O}/\text{H})$  is shown to be below 7.15 dex (Pustilnik et al. 2005; Izotov & Thuan 2007; Annibali et al. 2019). Since in such an advanced stage of merging, it is difficult to recover the pre-merger mass ratio, the fainter component parameters are adopted with large uncertainties.

One more XMP dwarf in the Lynx-Cancer void, J0943+3326 (AGC198691 = Leoncino) was found independently among the ALFALFA blind HI survey (Haynes et al. 2018) newly identified gas-rich objects (Hirschauer et al. 2016).

In addition, three new XMP dwarfs were found via their emission-line spectra in the SDSS data base and later were identified as representatives in nearby voids. In particular, J0015+0104, was found by Guseva et al. (2009, 2017) and was studied further as one of the Eridanus void dwarfs by Pustilnik et al. (2013) and Kniazev et al. (2018). Two more XMP dwarfs J0113+0052 and J2104-0035 were found in the SDSS by Izotov et al. (2006) and were further studied by Ekta et al. (2008) and Moiseev et al. (2010).

Two of the Lynx-Cancer void unusual dwarfs are members of the very gas-rich triplet J0723+36. Their MH  $I/L_B$  ratios,  $\sim 12$  and  $\sim 28$ , respectively, fall among the highest known values of this empirical parameter. The related estimates of their stellar mass fractions  $M_{\text{star}}/M_{\text{gas}} < 0.01$  (Chengalur & Pustilnik 2013) are also extremely low. Both dwarfs have very low H  $\alpha$  fluxes and their O/H ratios are hard to obtain. However, estimates of their possible evolutionary status allow one to assign them to the same group of unusual void dwarfs (Chengalur & Pustilnik 2013). Since they have no O/H values, we put them in Table 1 below the main group, separated by a horizontal line.

We notice that all these prototype very gas-rich XMP dwarfs have blue colours, namely  $(g-r)_0 \lesssim 0.20$ , and mostly  $(g-r)_0 \lesssim 0.15$ . Such colour indices correspond to the PEGASE (Fioc & Rocca-Volmerange 1999) stellar metallicity  $z = 0.0004$  instantaneous evolutionary tracks with a time since the (localized) star formation episode of  $\lesssim 1-2$  Gyr or to the time of continuous SF with constant SFR of  $\lesssim 3-5$  Gyr, depending on the adopted initial mass function and the  $(u-g)$  colour (Perepelitsyna et al. 2014).

At the bottom of Table 1, separated from the main table by a horizontal line, we also include two recently discovered very distant unusual compact star-forming galaxies with the record low gas O/H ratio and very blue continuum with no traces of old stellar populations, J0811+4730 and J1234+3901 (Izotov et al. 2018, 2019a). These dwarfs are probably the best candidates for so-called VYGs predicted in models (Tweed et al. 2018). Such XMP objects caught in the short phase of strong starburst are very rare as already mentioned in Section 1. They are similar in their strong starbursts to the well known much closer XMP BCGs IZw18 and SBS0335-052E.

The columns of Table 1 are as follows: Column 1 – brief IAU-type name; Column 2 – adopted parameter of gas  $12+\log(\text{O}/\text{H})$  with its  $1\sigma$  error; Column 3 – HI-mass to blue luminosity ratio, in solar units, MH  $I/L_B$ ; Column 4 –  $\mu_{B,0,c}$  (when known) central surface brightness, corrected for extinction in the Milky Way and inclination (Perepelitsyna et al. 2014); Column 5 – absolute blue magnitudes  $M_B$ , derived from  $B_{\text{tot}}$  in Column 10 and distance in Column 8; Column 6 – integrated colour  $(g-r)_0$ . This comes for J0015+0104 from Pustilnik et al. (2013), for J0706+3020 from Chengalur

et al. (2017), for J0926+3343, J0929+2502, J0723+3622, and J0723+3624 from Perepelitsyna et al. (2014), for J0943+3326 we adopt  $(g-r)$  presented in the SDSS DR14 data base (Abolfathi et al. 2018). For J0956+2850 (DDO68B), the range of colours for various parts of the assumed fainter component of the merger comes from Pustilnik, Tepliakova & Kniazev (2008); for J2104-0049, we adopt our unpublished measurement from the SDSS images; Column 7 –  $V_h$  the heliocentric velocity; Column 8 – distance to object, in Mpc, either known from TRGB estimate, or for the radial velocity based distance – accounting for the large peculiar velocity of the Local Sheet, up to  $\sim 350 \text{ km s}^{-1}$ , depending on the sky position (Tully et al. 2008). See PTM19 for more detail; Column 9 – log of mass of HI gas, in units of  $M_\odot$ ; Column 10 – estimate of log of stellar mass following the recipe by Zibetti, Charlot & Rix (2009), in units of  $M_\odot$ . These estimates come from Pustilnik et al. (2013), Perepelitsyna et al. (2014), Chengalur et al. (2017); Column 11 – total apparent  $B$ -band magnitude; Column 12 – notes with additional information and references for parameters in the table. Several entries in the table with lower accuracy are marked with a colon (:).

Summarizing the data in this table and in accord with our earlier conclusions on the group properties of these unusual void dwarfs with the lowest O/H ratios, we emphasize their low luminosity,  $M_B$  between  $\sim -9.5$  and  $-14.2$ , and medium to high MH  $I/L_B$ , from  $\sim 2$  up to 28. In most cases, they are related to LSB discs with blue colours. The full range of baryonic mass (gas plus stars) in known prototype XMP void dwarfs is  $(\sim 2-40) \times 10^7 M_\odot$ . The atomic gas HI along with atomic He (adopted as 30 per cent of HI) is dominant by mass over the stellar component by  $\sim 1.5-2$  orders of magnitude. Their dynamical masses  $M_{\text{dyn}}$  within the HI-radius at the surface density level of  $0.3 M_\odot \text{ pc}^{-2}$  are estimated only for several objects and typically comprise  $5-10 M_{\text{bary}}$ . The total masses of the related cold dark matter (CDM) haloes,  $M_{\text{vir}}$ , can be several to 10 times higher than  $M_{\text{dyn}}$  as argued in simulations by Hoeft et al. (2006). That is, the expected range of CDM halo masses for these XMP dwarfs is between  $<10^9$  and  $\sim 10^{10} M_\odot$ .

#### 4 CANDIDATE SELECTION CRITERIA AND THE LIST

We proceed with the selection of void XMP candidates based on the properties of known void XMP dwarfs summarized in the previous section. For this, we make the selection in several steps.

First, we use the NVG sample (PTM19) of 1354 galaxies residing in the Nearby Voids, briefly described in Section 2, to select objects in its low luminosity tail. This step is related to our previous results as explained below.

In the unbiased photometric and spectroscopic study of about a hundred galaxies residing in a nearby Lynx-Cancer void (Perepelitsyna et al. 2014; Pustilnik et al. 2016), we found that the most gas-rich dwarfs, with the lowest gas O/H ratio and *atypically* blue colours of stars at their periphery, are predominantly the *lowest* luminosity dwarfs. Their fraction among void galaxies is significantly elevated for the range of  $M_B > -13.2$ . However, inclusion in Table 1 of three prototype XMP dwarfs residing in other nearby voids pushes this limit to  $M_B$  of  $-14.2$ . This indicates that the latter cut can be more appropriate for picking up similar void XMP candidates. Thus, allowing a small margin in this cut, we adopt a  $B$ -band absolute magnitude limit of  $-14.3$ . This gives us an initial subsample of  $\sim 380$  of the NVG faint-end galaxies.

Secondly, we use publicly available parameters of this subsample to further select objects with substantially high value of MH  $I/L_B \gtrsim 1$ ,

in particular as obtained from HyperLEDA (Makarov et al. 2014)<sup>1</sup> and NED. At the first pass, we obtained several tens galaxies with  $MH\ i/L_B \gtrsim 3$ . Galaxies with that high a  $MH\ i/L_B$  ratio are quite rare. To be confident that this is not due to some errors, we checked for alternative total blue magnitudes  $B_{tot}$  in the literature, where possible. Also, we used the SDSS image data base. We obtained their total magnitudes in circular apertures in  $g, r$  filters and used the transform of Lupton et al. (2005) to derive their  $B_{tot}$ .

In more than half of such ‘gas-rich’ galaxies selected automatically, we found that the updated  $B_{tot}$ , taken either as a more reliable estimate in the literature, or estimated by us from the SDSS images, appear significantly brighter than given in HyperLEDA. For some of the checked objects, the value of  $HI$  flux in HyperLEDA was outdated and substantially larger than the more recent measurements. All these updates were taken into account for the final selection and the false ‘gas-rich’ galaxies were excluded. However, some of the errors in  $B_{tot}$  and  $HI$  flux for the selected XMP candidate objects were detected later, when a galaxy was already observed in our programme. Their  $MH\ i/L_B$  ratio seems to be smaller than 1. We kept, however, several such candidates in the list. Therefore, parameters of  $B_{tot}$  and  $M_B$  shown for the selected XMP candidates in Table 2 can differ significantly from those in the original NVG catalogue, which was based mostly on data from HyperLEDA.

Thirdly, where possible, we also determined SDSS integrated colours for the selected galaxies. We use colour  $g - r$ , corrected for the MW reddening, as an additional selection criterion, to cut-off the reddest objects. The goal of this additional criterion is to pick up the objects with a predominant contribution of light from a relatively young stellar population. However, we chose to extend significantly the colour range defined XMP prototype group. On the one hand, we want to account for possible uncertainties in the XMP candidate colour estimates. On the other hand, thanks to a wider range of  $(g - r)$ , we can examine how tightly the very low gas metallicity is related to galaxy colour. Therefore, we adopt as a colour selection criterion  $(g - r)_0 < 0.4$ . We also kept in the list several galaxies with somewhat doubtful  $(g - r)_0 > 0.4$  and large  $MH\ i/L_B$ .

As a result, from the original NVG subsample of  $\sim 380$  faint void galaxies, applying additional selection criteria, we compiled a subsample of 60 void dwarfs for further optical spectroscopy (see Table 2).

For several of these candidates, SDSS spectra of the central part of the galaxy are available. Due to the redshift range of our sample, the important line  $[O\ II]\lambda 3727$  used in the classical  $T_e$  method to estimate  $O/H$  in  $H\ II$  regions is outside the SDSS spectral coverage. However, the other strong lines can provide useful information on the expected level of the oxygen abundance. In particular, we exploit the equations (1) and (3) from Izotov et al. (2019b) to look for potential XMP candidates. According to their equation (1), galaxies with parameter  $R_{23} \lesssim 4$  should have  $12 + \log(O/H) \lesssim 7.4$ . Here,  $R_{23} = [I([O\ III]\lambda 4959) + I([O\ III]\lambda 5007) + I([O\ II]\lambda 3727)]/I(H\ \beta)$ .  $I([O\ II]\lambda 3727)$  is fitted with their equation (3), namely  $I([O\ II]\lambda 3727) = 20 \times I([N\ II]\lambda 6584)$ , when  $I([N\ II]\lambda 6584)/I(H\ \beta) < 0.1$ .

This information was also taken into account in our selection of void XMP candidates to include several objects with the value of  $MH\ i/L_B < 1$  or without  $HI$  data, or with  $g - r$  somewhat redder than  $\sim 0.4$ . Among XMP candidates in Table 2 with SDSS spectra,

an estimate of  $O/H$  is available only for one, J1522+4201 (Izotov et al. 2019b).

Besides, one more galaxy with published  $O/H$ , KK246, was included by us as an XMP void candidate according to our selection criteria. Its value of  $12 + \log(O/H) = 8.2$  (Nicholls et al. 2014) appears a strong upward outlier with respect of the value expected for its properties. Therefore, it deserves an independent check.

For several candidates in Table 2, after our additional checks, the parameter  $MH\ i/L_B$  appeared substantially lower than the one adopted initially. However, since their spectra were already obtained, we kept them in the list. This allows us to address the diversity of properties of void XMP dwarfs.

The selected candidates for spectral observations are listed in Table 2. The columns include the following information: Column 1 – *id* number; Column 2 – galaxy name in the NVG catalogue, mainly adopted from the HyperLEDA database; Column 3 – J2000 epoch coordinates; Column 4 – heliocentric velocity in  $km\ s^{-1}$ ; Column 5 – distance in Mpc (either measured independently of velocity, or with the use of the peculiar velocity correction similar to that described for Table 1); Column 6 – estimate of total  $B$ -band magnitude; Column 7 – the related absolute magnitude  $M_B$ ; Column 8 –  $HI$  mass to the blue luminosity ratio  $MH\ i/L_B$ , in solar units; Column 9 –  $\log MH\ i$  and Column 10 –  $\log(M_*)$ , both in solar masses; Column 11 – notes. Where possible, we measured (similar to Perepelitsyna et al. 2014) integrated colours of the examined candidates. Most estimates of  $M_*$  are obtained via the method of Zibetti et al. (2009), based on our photometry of the candidate galaxies available in the SDSS image data base (Abolfathi et al. 2018). For several galaxies outside the SDSS footprint, where possible, we performed similar photometry on the public data bases of PanSTARRS PS1 (Flewelling et al. 2016) and Dark Energy Survey (DES DR1) (Abbott et al. 2018). For several galaxies not in these data bases, we used estimates of  $M_*$  from Gurovich et al. (2010) for HIPASSJ0653-73 (Kirbi et al. 2008); Kreckel et al. (2011) for KK246 and Karachentsev, Kaisina & Makarov (2014) for ESO238-005.

As one can see, XMP void candidates in Table 2 fall in a wide range of distances from  $\sim 5$  to 25 Mpc. Their  $B_{tot}$  range between  $\sim 15.5$  and  $\sim 20.0$  mag. Their absolute blue magnitudes  $M_B$  fall between  $-10.3$  and  $-14.3$  mag. The ratio  $MH\ i/L_B$  for the great majority of selected candidates is between  $\sim 1$  and 6.5. However, for a couple of objects it was estimated as  $\sim 0.6$ . The baryonic mass range of the candidates is close to that of XMP prototypes, i.e.  $(2-40) \times 10^7 M_\odot$ . Only four objects have this parameter in the range  $(0.6-2) \times 10^7 M_\odot$ . As follows from comparison of mass estimates of  $HI$  and stars in Columns 9 and 10, for 48 galaxies that have both estimates, the ratio  $M(HI + He)/M_*$  for the candidate galaxies varies over a wide range, with extremes of  $\sim 2$  and  $\sim 100$ , with the median of 12, and with half of the entries between 5 and 26. The future analysis of measured gas  $O/H$  in these XMP candidates along with their parameters in Table 2 will allow us to improve the current selection criteria and to make the spectral follow-ups more efficient.

In Figs 1 and 2, we show distributions of parameters  $M_B$ ,  $MH\ i/L_B$ , integrated colour  $(g - r)_0$  and the ratio  $R_{23}$  for both samples: prototype XMP void dwarfs (hashed histograms) and the sample of selected candidate void XMP dwarfs from Table 2 (thick line histograms). As one can see, the distribution of  $M_B$  for the candidate sample matches well that of the prototype objects. However,  $\sim 2/3$  of candidates have  $M_B < -13.0$ , whereas the majority of prototype XMP objects are fainter than  $M_B = -13.0$ . As for the ratio  $MH\ i/L_B$ ,

<sup>1</sup><http://leda.univ-lyon1.fr>

**Table 2.** List of nearby void galaxies candidate XMP dwarfs.

| #  | Name           | J2000 Coordinate | $V_h$            | $D$<br>(Mpc) | $B_{\text{tot}}$<br>(mag) | $M_B$<br>(mag) | $\frac{MH1}{L_B}$ | logMH I | log $M_*$ | Notes                       |
|----|----------------|------------------|------------------|--------------|---------------------------|----------------|-------------------|---------|-----------|-----------------------------|
| 1  | 2              | 3                | 4                | 5            | 6                         | 7              | 8                 | 9       | 10        | 11                          |
| 1  | AGC102728      | J000021.4+310119 | 566              | 9.4          | 19.38                     | -10.65         | 2.46              | 6.85    | 5.82      |                             |
| 2  | PGC000083      | J000106.5+322241 | 542              | 9.1          | 17.14                     | -12.86         | 1.41              | 7.48    | 6.19      |                             |
| 3  | PGC000389      | J000535.9-412856 | 1500             | 17.5         | 17.98                     | -13.30         | —                 | —       | —         | No HI data                  |
| 4  | AGC748778      | J000634.3+153039 | 258              | 6.3          | 18.95                     | -10.30         | 2.30              | 6.66    | 5.40      | D(TRGB)                     |
| 5  | PGC736507      | J000936.2-285138 | 898 <sup>a</sup> | —            | 19.14                     | -10.95         | —                 | —       | —         | not NVG object, wrong $V_h$ |
| 6  | PISCESA        | J001446.0+104847 | 235              | 5.6          | 17.98                     | -11.14         | 2.92              | 7.05    | 5.74      | D(TRGB)                     |
| 7  | HIPASSJ0021+08 | J002041.7+083655 | 693              | 9.9          | 17.10                     | -13.37         | 1.21              | 7.63    | 6.72      |                             |
| 8  | AGC104208      | J004142.5+125934 | 676              | 10.1         | 19.66                     | -10.74         | 3.45              | 7.01    | 5.92      |                             |
| 9  | AGC104227      | J005823.7+041825 | 1198             | 16.9         | 18.12                     | -13.11         | 2.13              | 7.76    | 6.56      |                             |
| 10 | PGC493444      | J010718.0-475633 | 837 <sup>a</sup> | —            | 19.47                     | -10.56         | —                 | —       | —         | not NVG object, wrong $V_h$ |
| 11 | PGC1190331     | J010910.1+011727 | 1094             | 15.4         | 17.20                     | -13.49         | 2.24              | 7.94    | 7.04      |                             |
| 12 | AGC411446      | J011003.7-000036 | 1137             | 15.9         | 19.53                     | -11.59         | 5.14              | 7.53    | 5.66      |                             |
| 13 | AGC114584      | J011250.5+015207 | 1089             | 15.4         | 18.17                     | -13.14         | 1.90              | 7.62    | 6.02      |                             |
| 14 | PISCESB        | J011911.7+110718 | 616              | 8.9          | 17.63                     | -12.45         | 2.58              | 7.52    | 6.41      | D(TRGB)                     |
| 15 | AGC122400      | J023122.1+254245 | 938              | 15.5         | 18.92                     | -12.45         | 3.66              | 7.73    | —         |                             |
| 16 | AGC124137      | J023137.0+093144 | 897              | 14.0         | 17.98                     | -13.12         | 2.06              | 7.78    | 6.72      |                             |
| 17 | AGC124076      | J023730.2+212246 | 950              | 15.5         | 17.60                     | -13.90         | 2.51              | 8.15    | —         |                             |
| 18 | AGC121174      | J023816.5+295423 | 693              | 12.4         | 16.89                     | -14.12         | 6.55              | 8.39    | 7.65      |                             |
| 19 | AGC123223      | J024709.3+100516 | 767              | 12.4         | 17.52                     | -13.77         | 1.79              | 7.99    | 7.01      |                             |
| 20 | AGC124609      | J024928.4+344429 | 1588             | 25.0         | 18.00                     | -14.25         | 1.31              | 8.05    | 7.07      |                             |
| 21 | AGC124629      | J025605.6+024831 | 794              | 12.4         | 19.46                     | -11.50         | 1.72              | 7.22    | 5.88      |                             |
| 22 | KKH18          | J030305.9+334139 | 210              | 4.8          | 17.11                     | -12.01         | 1.90              | 7.20    | 6.49      | D(TRGB)                     |
| 23 | AGC132121      | J030644.1+052008 | 678              | 11.0         | 17.30                     | -13.53         | 1.62              | 7.86    | 6.79      |                             |
| 24 | PGC1166738     | J030646.9+002811 | 710              | 11.2         | 17.94                     | -12.67         | 0.89              | 7.21    | 6.39      |                             |
| 25 | PGC013294      | J033556.8-451129 | 737              | 7.3          | 16.35                     | -13.36         | —                 | —       | 6.82      | D(TRGB) No HI data          |
| 26 | ESO121-020     | J061554.3-574332 | 582              | 6.1          | 15.87                     | -13.20         | 3.87              | 8.06    | 6.60      | D(TRGB)                     |
| 27 | PGC385975      | J061608.5-574551 | 554              | 6.1          | 17.10                     | -11.79         | 2.49              | 7.38    | 6.03      | Comp. of ESO121-020         |
| 28 | HIPASSJ0653-73 | J065352.7-734228 | 1208             | 13.5         | 17.90                     | -13.14         | 5.39              | 8.19    | 8.03      |                             |
| 29 | AGC174605      | J075021.7+074740 | 351              | 9.9          | 17.82                     | -12.25         | 1.33              | 7.21    | 6.44      | D(TRGB)                     |
| 30 | AGC188955      | J082137.0+041901 | 758              | 12.8         | 17.57                     | -13.04         | 0.86              | 7.40    | —         | Very blue                   |
| 31 | AGC189201      | J082325.6+175457 | 1475             | 23.4         | 19.24                     | -12.74         | 4.03              | 7.89    | 6.09      |                             |
| 32 | AGC198454      | J092811.3+073237 | 1373             | 21.0         | 18.51                     | -13.28         | 1.25              | 7.84    | 6.54      |                             |
| 33 | SDSSJ0947+3905 | J094758.5+390510 | 1501             | 24.9         | 18.03                     | -14.01         | 3.20              | 8.17    | 7.22      | In triplet with MRK407      |
| 34 | AGC191803      | J094805.9+070743 | 526              | 9.2          | 16.79                     | -13.14         | 1.38              | 7.58    | 7.01      |                             |
| 35 | PGC1230703     | J100425.1+023331 | 1126             | 17.1         | 17.71                     | -13.53         | 0.56              | 7.16    | 7.04      |                             |
| 36 | PGC1178576     | J102138.9+005400 | 701              | 11.0         | 17.35                     | -13.04         | 1.44              | 7.58    | 6.40      |                             |
| 37 | AGC208397      | J103858.1+035227 | 763              | 11.9         | 19.95                     | -10.56         | 5.75              | 7.18    | 5.60      |                             |
| 38 | PGC044681      | J125956.6-192441 | 827              | 7.3          | 17.50                     | -12.16         | 4.88              | 7.77    | 6.64      | D(TRGB)                     |
| 39 | PGC166153      | J130642.5+180008 | 1573             | 22.5         | 18.03                     | -13.82         | 5.11              | 8.42    | 7.77      |                             |
| 40 | AGC233627      | J131953.0+134824 | 937              | 13.4         | 17.78                     | -12.94         | 2.76              | 7.81    | 6.87      |                             |
| 41 | PGC135827      | J132812.2+021642 | 1008             | 13.5         | 16.51                     | -14.24         | 1.62              | 8.09    | 7.20      |                             |
| 42 | AGC238847      | J134509.7+272011 | 901              | 13.5         | 18.57                     | -12.21         | 2.64              | 7.47    | 6.40      |                             |
| 43 | AGC239144      | J134908.2+354434 | 1366             | 20.4         | 19.06                     | -12.54         | 3.17              | 7.70    | 6.01      |                             |
| 44 | AGC716018      | J143048.7+070926 | 1365             | 19.1         | 18.18                     | -13.19         | 3.72              | 8.08    | 6.98      |                             |
| 45 | AGC249590      | J144031.6+341601 | 1489             | 21.7         | 18.45                     | -13.27         | 2.70              | 7.93    | 6.62      |                             |
| 46 | SDSSJ1444+4242 | J144449.8+424254 | 634              | 10.9         | 19.11                     | -10.54         | —                 | —       | 5.71      | Near UGC9497, no HI data    |
| 47 | PGC2081790     | J144744.6+363017 | 1226             | 18.1         | 17.66                     | -13.67         | 1.49              | 7.83    | 6.95      |                             |
| 48 | AGC009540      | J144852.0+344243 | 801              | 12.1         | 16.25                     | -14.27         | 2.29              | 8.26    | 7.09      |                             |
| 49 | AGC249197      | J144950.7+095630 | 1809             | 24.2         | 18.69                     | -13.48         | 2.45              | 7.92    | 6.75      |                             |
| 50 | J1522+4201     | J152255.5+420158 | 608              | 9.8          | 17.87                     | -12.18         | —                 | —       | 6.63      | No HI data, SDSS spect      |
| 51 | AGC258574      | J154507.9+014822 | 1523             | 19.3         | 17.72                     | -13.09         | 2.60              | 8.20    | 7.18      |                             |
| 52 | SDSSJ1705+3552 | J170517.4+355222 | 992              | 14.1         | 16.99                     | -13.85         | —                 | —       | 7.20      | No HI data, SDSS spect      |
| 53 | HIPASSJ1738-57 | J173842.9-571525 | 858              | 7.3          | 16.62                     | -13.06         | 2.18              | 7.73    | —         |                             |
| 54 | KK246          | J200357.4-314054 | 431              | 7.1          | 17.07                     | -13.28         | 2.30              | 8.02    | 7.70      | D(TRGB)                     |
| 55 | SDSSJ2103-0049 | J210347.2-004950 | 1411             | 17.4         | 17.44                     | -14.02         | 1.36              | 7.83    | 7.33      |                             |
| 56 | PGC1016598     | J213902.9-073443 | 1283             | 15.4         | 18.63                     | -12.43         | —                 | —       | 6.63      | No HI data                  |
| 57 | AGC321307      | J221404.7+254052 | 1152             | 16.2         | 18.29                     | -13.07         | 2.85              | 7.86    | 7.01      |                             |

**Table 2** – *continued*

| #  | Name       | J2000 Coordinate | $V_h$ | $D$<br>(Mpc) | $B_{\text{tot}}$<br>(mag) | $M_B$<br>(mag) | $\frac{\text{MH}}{L_B}$ | $\log \text{MH}$ | $\log M_*$ | Notes                |
|----|------------|------------------|-------|--------------|---------------------------|----------------|-------------------------|------------------|------------|----------------------|
| 1  | 2          | 3                | 4     | 5            | 6                         | 7              | 8                       | 9                | 10         | 11                   |
| 58 | ESO238–005 | J222230.5–482414 | 706   | 8.0          | 15.53                     | –13.59         | 2.16                    | 8.34             | 8.19       | D(TRGB)              |
| 59 | AGC335193  | J230349.0+043113 | 1125  | 16.1         | 17.25                     | –14.03         | 0.56                    | 7.58             | 7.25       |                      |
| 60 | PGC4581795 | J235419.3+105647 | 943   | 13.2         | 17.52                     | –13.41         | 1.04                    | 7.53             | 6.97       | AGC332123 = F750–V01 |

*Notes.* Candidate galaxy parameters are presented as follows: Column 1: *id* number; Column 2: common name; Column 3: J2000 coordinates; Column 4: radial velocity in  $\text{km s}^{-1}$ ; Column 5: adopted distance (see the table description); Column 6: total  $B$  magnitude; Column 7: absolute  $B$  magnitude; Column 8:  $\text{MH}/L_B$  ratio in solar units; Column 9: logarithm of  $\text{MH}$  in  $M_\odot$ ; Column 10: logarithm of  $M_*$  in  $M_\odot$ .

<sup>a</sup>Galaxies marked as ‘wrong  $V_h$ ’ appear distant based on SALT data.

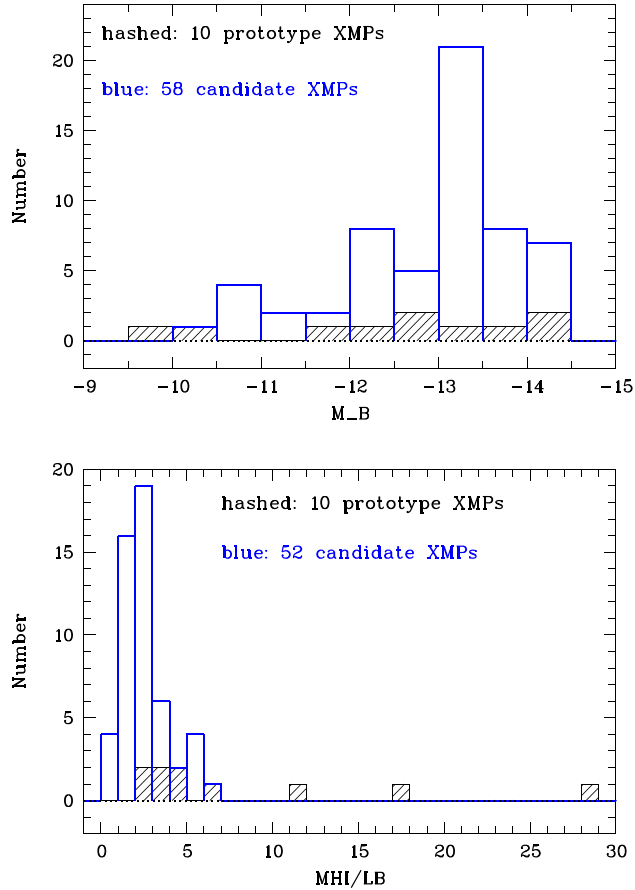


**Figure 1.** Comparison of observational properties of 10 prototype XMP void galaxies (hashed histograms) and XMP void candidates with available data (blue thick histograms). Top panel: Distribution of absolute blue magnitudes  $M_B$ . Bottom panel: Distribution of ratio  $\text{MH}/L_B$  (in solar units).

about 2/3 of candidates fall in the range of  $\text{MH}/L_B$  for prototype galaxies, but the remaining candidates have somewhat lower gas content. An even larger difference is seen for the distribution of colour  $(g-r)_0$ . Only  $\sim 40$  percent of candidates have  $(g-r)_0$  as blue as for the prototype objects. As we already noticed in the description of our selection, we decided to extend parametric space for candidate XMP in order to account for probable errors in parameter estimates and for the limited size of the XMP void prototype group that may affect its representativity.

The ratio  $R_{23}$  was estimated only for a dozen of candidates with available SDSS spectra. Since the line  $[\text{O II}]\lambda 3727 \text{ \AA}$  was outside

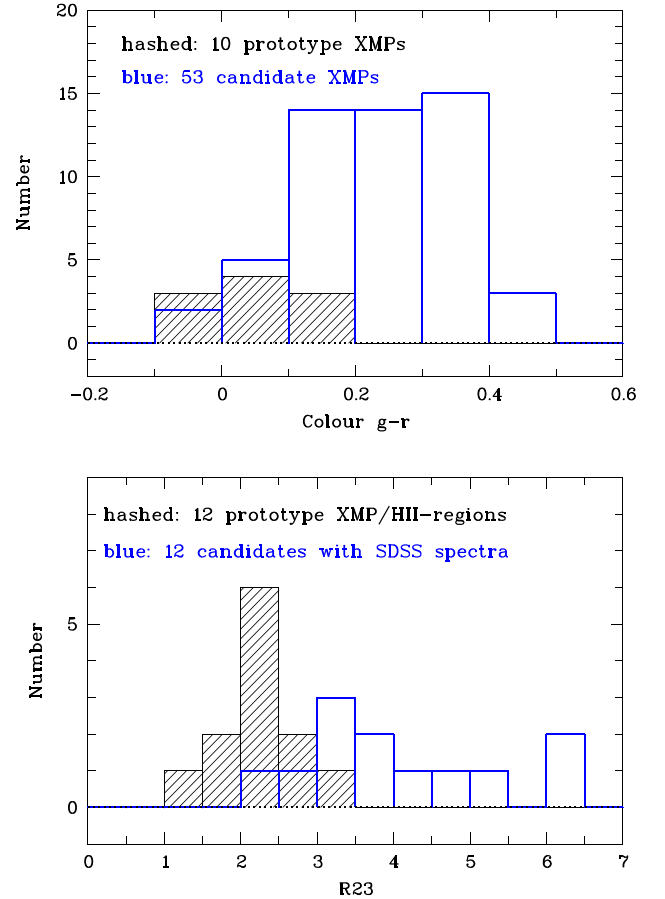


**Figure 2.** Comparison of observational properties of 10 prototype XMP void galaxies (hashed histograms) and XMP void candidates with available data (blue thick histograms). Top panel: Distribution of the MW-extinction-corrected integrated colour  $(g-r)_0$ . Bottom panel: Distribution of parameter  $R_{23}$  for 12 H II-regions in prototype XMP galaxies and 12 candidate XMP galaxies. See the text for more detail.

the SDSS wavelength range, its flux was estimated via the flux of  $[\text{N II}]\lambda 6584 \text{ \AA}$  as explained above. Since the scatter in the relation between the fluxes of these two lines can be a factor of  $\sim 2$ , the related estimate of  $R_{23}$  can also have large uncertainty and should be treated only as an indicative one. One can see that for prototype XMP dwarfs  $R_{23}$  fall into the range between 1.3 and 3.5. For a number of XMP candidates,  $R_{23}$  falls in the same range. However, in general their  $R_{23}$  appear to be larger than for the prototype group.

In Figs 3 and 4, we present thumbnail images of 46 galaxies within the SDSS footprint. They were obtained via the SDSS data base finding chart service. In Fig. 5, we present finding charts for 14 void galaxies outside the SDSS zone. They are combined from the Digital Sky Survey (DSS) *B* and *R* images.

## 5 DISCUSSION

### 5.1 Scenarios for various types of XMP dwarfs

It is worth underlining that XMP dwarfs can have rather different evolutionary histories. Four physical mechanisms resulting in the observed very low gas metallicity in galaxies have been proposed and have observational support. Two of them define the secular galaxy evolution. These are (1) a less efficient star formation in galaxies of smaller mass and the related slower metal production (so-called downsizing) and (2) the increased metal loss via the galactic wind in smaller galaxies due to their shallow galaxy gravitational well (e.g. Garnett 2002). One can also suggest the interplay between the two mechanisms.

In periods of elevated star formation, the collective effect of multiple SNe leads to galaxy winds that efficiently evacuate the fresh metals into the IGM. As shown by McQuinn et al. (2015), the nearby very low mass XMP dwarf Leo P, with  $12+\log(\text{O}/\text{H}) = 7.17$  dex, has lost  $\sim 95$  per cent of its produced metals during its long life. This mechanism is quite general and seems to contribute substantially to the known direct relation between metallicity and galaxy mass or luminosity. One such tight relation is exemplified by Berg et al. (2012) using a well-defined sample of late-type galaxies in the Local Volume with the  $M_B$  range of  $-10.5$  to  $-18.5$ . It extends to even lower  $M_B$ , since the very low value of  $\text{O}/\text{H}$  for Leo P with  $M_B = -8.8$  matches the relation of  $12+\log(\text{O}/\text{H})$  versus  $M_B$  from Berg et al. (2012) well.

Two other mechanisms, leading to significantly reduced gas metallicity, sometimes falling into the XMP regime, are transient and more localized, and thus can be considered as additional factors affecting the secular evolution of gas metallicity. The characteristic time-scale for erasing the temporary  $\text{O}/\text{H}$  drop is comparable to the gas disc rotational period. The third scenario is expected for the SF bursts in the periphery of galaxy discs induced by accretion events of very metal-poor ambient intergalactic gas with  $Z \sim (0.01-0.02) Z_\odot$  (the so-called cold accretion along cosmic web filaments, e.g. Sanchez Almeida et al. 2016; Ceverino et al. 2016). Due to the admixture of the fresh ambient gas, the observed metallicity in an SF region can be substantially reduced with respect to the global value for a galaxy in question.

A similar mechanism is related to the transient event of a (central) starburst induced by interaction with a galaxy disturber (Ekta & Chengalur 2010). As shown by e.g. Thuan, Lecavelier des Etanges & Izotov (2005), the distant periphery of discs in late-type dwarf galaxies can keep metallicity at the levels of the ambient IGM. When this gas is substantially disturbed, it can lose stability and inflow into the galaxy centre with the subsequent mixture and an induced starburst. Thus, this phenomenon can substantially dilute the metallicity of the induced SF burst and temporarily appear as a very metal-poor object.

As follows from information in Column 12 of Table 1, a substantial fraction of prototype XMP void dwarfs appear to be in pairs or triplets. Here, we provide the references supporting this evidence. J0113+0052 is suggested as a minor merger due to the detached  $\text{H}\alpha$  kinematics in its southern component (Moiseev et al. 2010) and highly disturbed HI morphology and kinematics (Ekta

et al. 2008). J0706+3030 is very likely a separate faint component in a merging triplet, UGC3672 (Chengalur et al. 2017). J0943+3326 (AGC198691), with a radial velocity difference of only  $37 \text{ km s}^{-1}$  and a projected distance of  $\sim 40 \text{ kpc}$  at the adopted  $D = 10.8 \text{ Mpc}$  (Hirschauer et al. 2016; Pustilnik et al. 2016), has clearly disturbed HI gas and is very likely a fainter companion of a nearby more massive dwarf, UGC5186. J0956+2850 (DDO68B), an outer part of the well-known XMP galaxy, DDO68 (Pustilnik et al. 2005; Ekta et al. 2008; Annibali et al. 2016; Makarov et al. 2017), is treated as a detectable remnant of a recent minor merger. J2104-0035, despite being well isolated, appears disturbed in HI GMRT maps. This led Ekta et al. (2008) to suggest that it could be an advanced merger. Finally, two extremely gas-rich dwarfs with unknown gas metallicity, J0723+3622 and J0723+3624, are smaller members of a triplet, J0723+36, near a void center (Chengalur & Pustilnik 2013).

Therefore, in general, the latter two mechanisms are expected to contribute to the observed low metallicity of void XMP dwarfs. However, in voids, significantly reduced gas metallicity can occur due to the specific environment and related conditions of galaxy formation and evolution. They include the late formation of low-mass dark matter haloes and the reduced SFR due to rare galaxy interactions. Thus, the very fact that a galaxy resides in a void, increases the possibility of its discovery as a less evolved object. In addition, the above-mentioned processes of transient metallicity reduction can increase the probability of finding void XMP dwarfs.

### 5.2 Very Young Galaxies

As formulated in the Introduction section, the main goal of this project is the search for new unusual void dwarfs resembling Very Young Galaxies in their properties. These are expected to exist in the Local Universe according to simulations of Tweed et al. (2018). They are defined as objects that formed more than half their stellar mass during the last  $\sim 1 \text{ Gyr}$ .

Izotov et al. (2018, 2019a) show from examples of the two record-low XMP star-forming galaxies that the best candidates for objects without traces of old stellar populations appear to be the lowest metallicity dwarfs. This is consistent with the idea that their extremely low metallicity is related to the short time elapsed, since the beginning of their main SF episode and the related low metal enrichment of their gas.

A similar conclusion was drawn in our study of dwarfs in the Lynx-Cancer void (Perepelitsyna et al. 2014; Pustilnik et al. 2016). Namely, we found that some of the most metal-poor void dwarfs, with gas  $\text{O}/\text{H}$  approaching  $1/50-1/30$  of the solar value, show unusually blue *ugri* colours in the outer parts, outside the regions of current SF. In contrast to the majority of other void galaxies, in two-colour diagrams they appear close to the positions corresponding to the *PEGASE* evolutionary tracks for ages of star formation episodes of  $\lesssim 1-3 \text{ Gyr}$ . In the accompanying paper (in preparation), we explore colours of the underlying LSB discs of newly discovered void XMP dwarfs. Based on the available SDSS images, we show that several of them have similar *ugri* colours corresponding to relatively small ages of visible stellar population. However, due to their LSB nature and the faint magnitudes, getting deeper images of these XMP objects and more accurate colours will be crucial for a more convincing conclusion.

On the other hand, as our previous study shows (Pustilnik et al. 2016), voids provide a conducive environment for slower galaxy evolution and related reduced gas metallicity in comparison to similar objects in denser environments. Recent models (Einasto et al. 2011) and *N*-body simulations with higher mass resolution

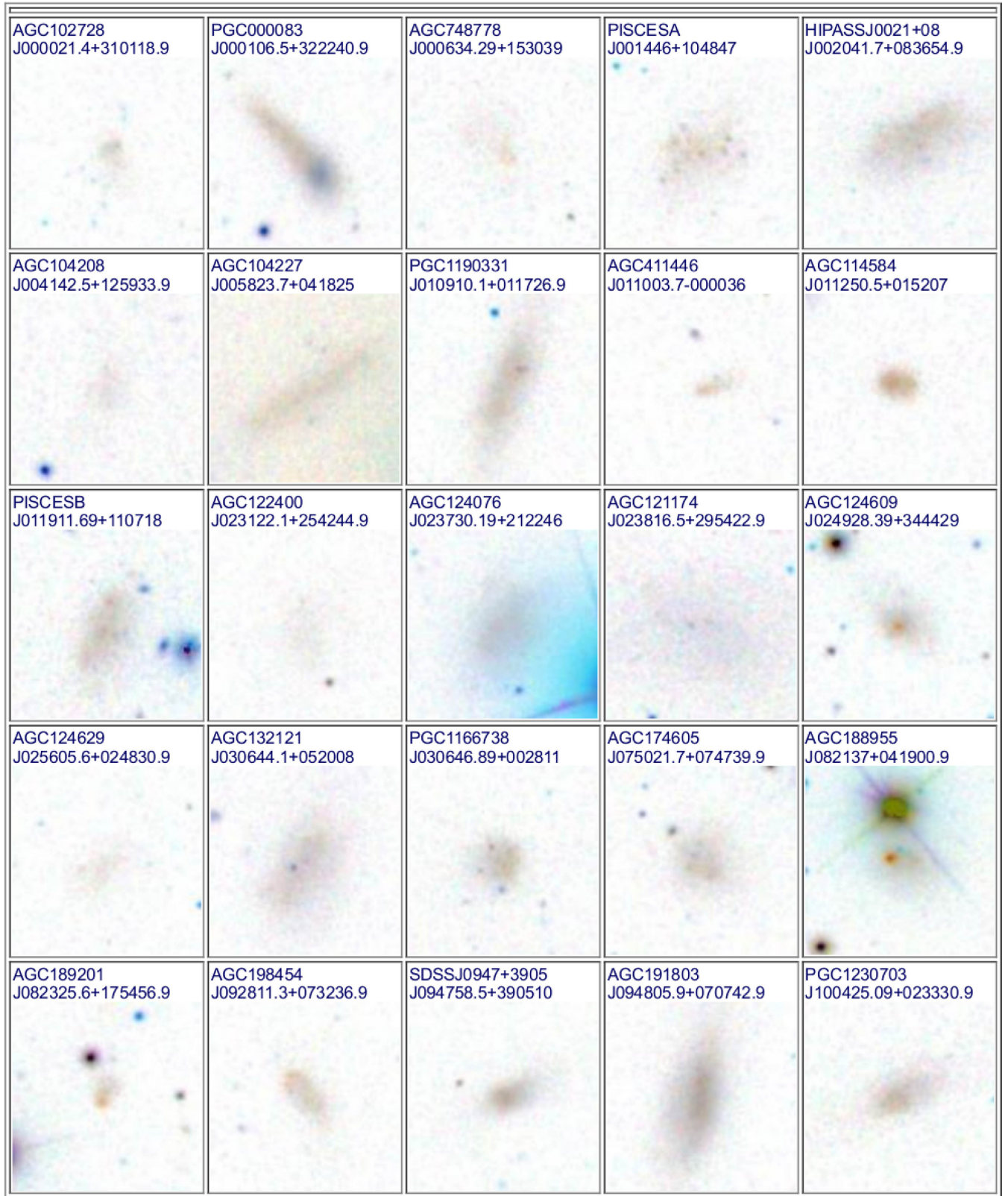


**Figure 3.** SDSS *gri* colour finding charts of NVG XMP candidates falling within the SDSS footprint. Colours are inverted to better see very low surface brightness objects. The first 25 galaxies are shown in RA order. The side of the box is  $\sim 50$  arcsec. North is up and east is to the left.

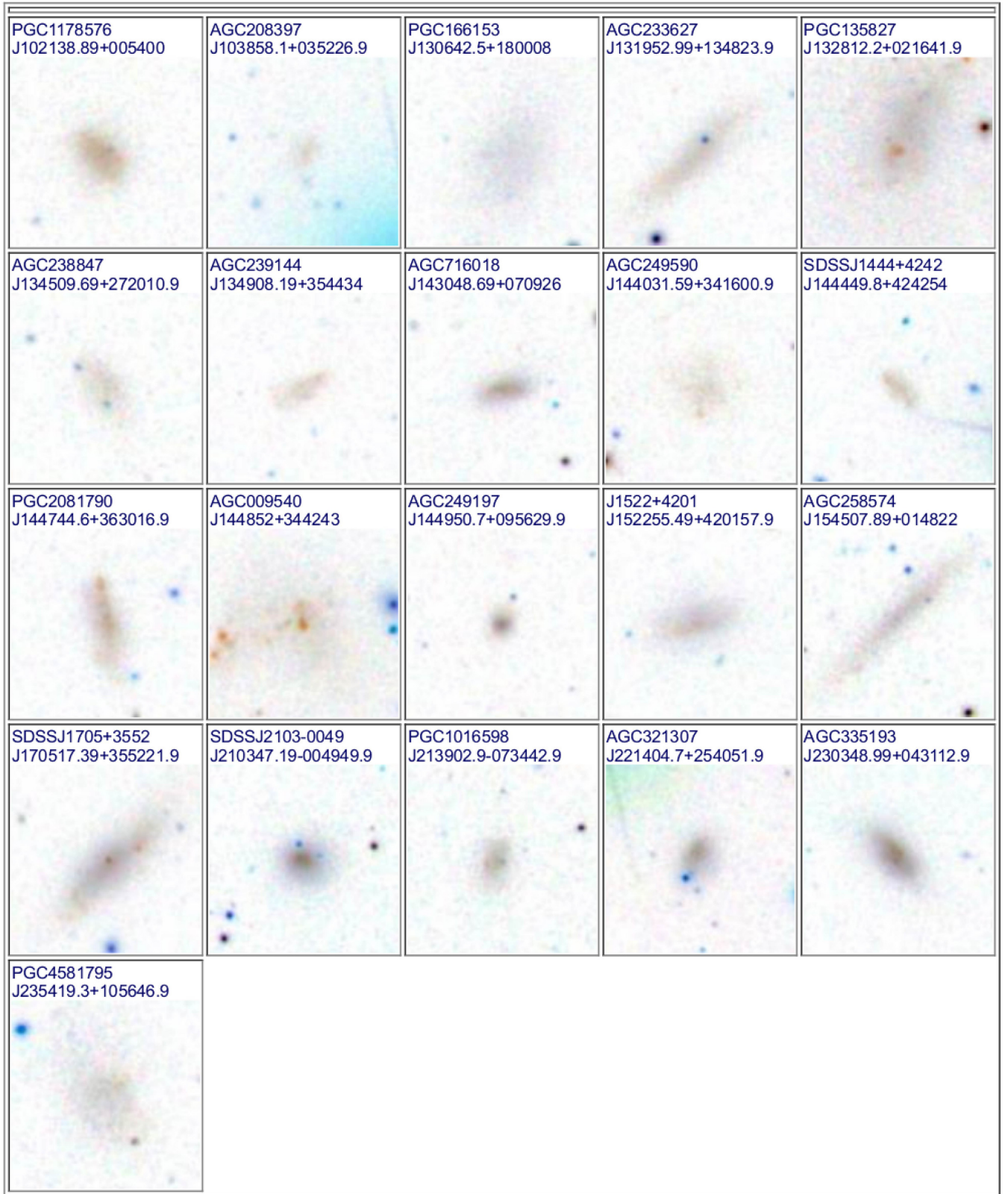


**Figure 4.** SDSS *gri* colour finding charts of NVG XMP candidates falling within the SDSS footprint. Colours are inverted to better see very low surface brightness objects. The last 21 galaxies are shown in RA order. The side of the box is  $\sim 50$  arcsec.

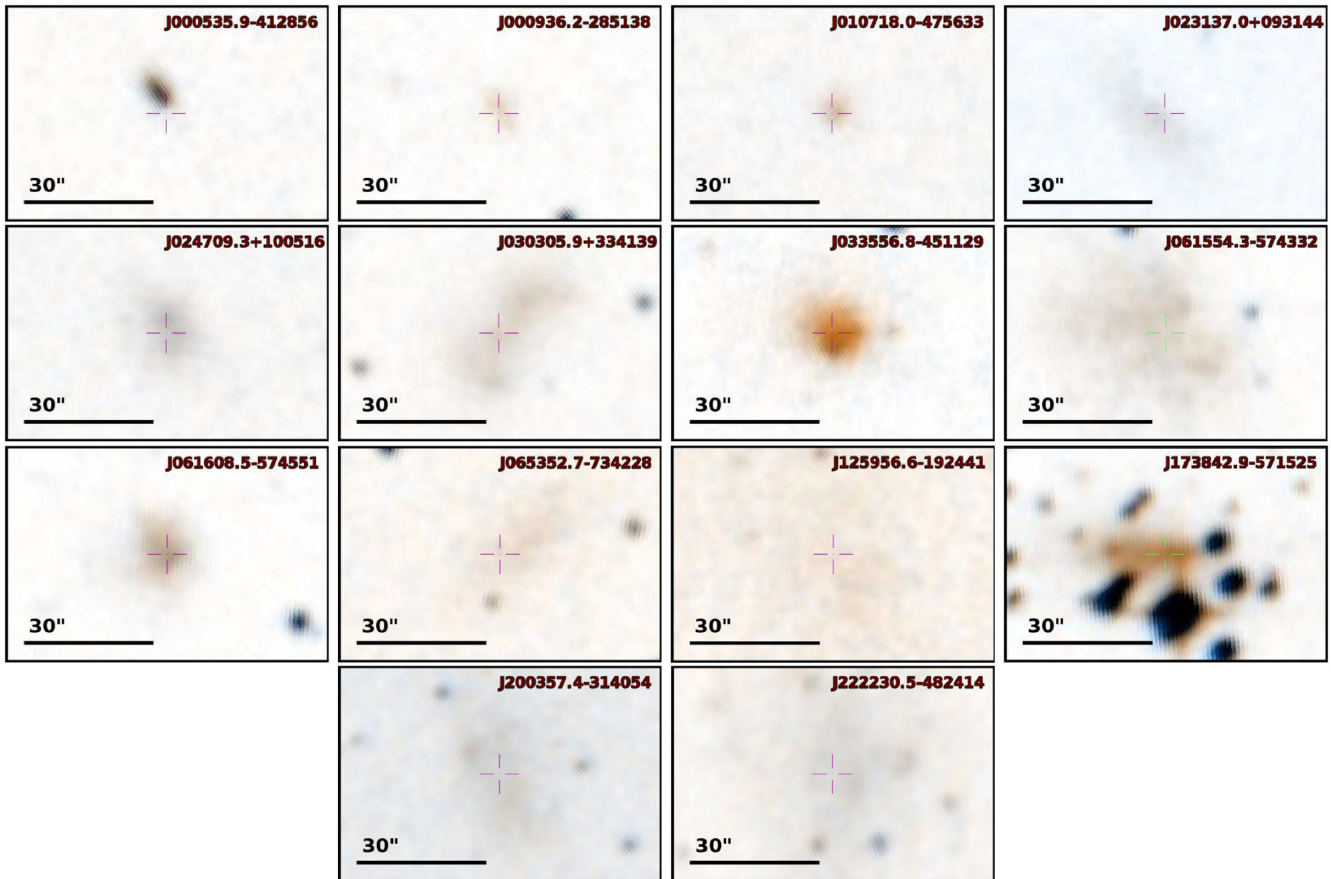


**Figure 5.** Finding charts of 14 NVG XMP candidates falling outside the SDSS footprint. Colours are inverted to better see very low surface brightness objects. Galaxies are shown in RA order. The bar in the box shows the angular scale.

(Rieder et al. 2013) also indicate the long time-scale effect of void environments. In particular, they predict a significant lag in the epoch of formation of lower mass DM haloes in voids with respect to similar epochs in denser environments. The expected delayed galaxy formation in voids is the natural cause of the observed reduced gas metallicity of void galaxies in addition to the four mechanisms discussed above.

## 6 SUMMARY AND CONCLUSIONS

The search for the most metal-poor dwarfs has been a popular direction in extragalactic research over almost half a century. In connection with the recent model predictions of rare VYGs, this work is even more relevant since it allows the observed number of such objects to be related to the expected numbers in different variants of possible cosmological models.

As discussed in Sections 3 and 5.2, some of the prototype void XMP dwarfs, as well as IZw18C, have properties that resemble those of VYGs predicted in simulations. Looking ahead, we state that several of our new void XMP galaxies presented in the accompanying papers are very similar in their properties to the prototype XMP galaxies. Therefore, systematic methods for finding gas-rich XMP dwarfs as the best proxies for VYGs can provide us with an opportunity to estimate a lower limit for the real fraction of VYGs in the nearby Universe, and in this context are potentially promising as one of the observational approaches to the VYG issue.

Summarizing the presented results and related discussion, we draw the following conclusions:

(i) The NVG sample provides us with a new opportunity to search for unusual XMP gas-rich dwarfs in voids, similar to known prototype XMP dwarfs.

(ii) For a more efficient search for new XMP dwarfs among objects in the NVG sample, we summarize the observational properties of eight known void XMP dwarfs (prototype objects) and two similar very gas-rich dwarfs without O/H and use them to separate the most probable void XMP candidates. Most of the necessary data for the selected candidates are obtained from the public data bases HyperLEDA, NED, SDSS and from the literature, and when possible, have been checked and updated by the authors.

(iii) The main selection criteria, as outlined in Section 4, are the similarity in properties to the prototype XMP dwarfs, namely the residence in nearby voids, the low luminosity, the elevated H $\alpha$ -content, and the blue/bluish colours. The available information on galaxy spectra with an indication of possible very low O/H was used as well as an additional criterion. As a result, we identify 60 void XMP candidates within the  $M_B$  range of  $[-10.3, -14.3]$  for a subsequent more careful study.

(iv) The suggested selection method has proved to be very efficient. This is supported by the results of the spectroscopy for half of the selected XMP candidates presented in two accompanying papers (Pustilnik et al. 2020). A dozen new void dwarfs with  $12+\log(\text{O}/\text{H}) \lesssim 7.3$  dex were found. Six of them have  $12+\log(\text{O}/\text{H})$  in the range of  $\sim 7.0$ – $7.17$  dex. Their properties are very similar to those of void

gas-rich XMP prototypes. The additional checks and constraints of the mass of old stellar population for this group should provide the better understanding of their origin and evolution. At the moment, the latter objects seem to be the best known nearby proxies of predicted in models VYGs.

(v) Since the original NVG sample is a volume limited one and includes all known galaxies, one can estimate the selection function and obtain realistic estimates of the sample completeness for various stellar masses. However, to further exploit the potential of these very gas-rich XMP dwarfs for the issue of VYGs, we need in some steps to confirm their direct relation to the simulated VYGs. Hopefully, this will allow for a more realistic estimate of a lower limit of the number of potential VYG objects in various ranges of galaxy stellar or baryonic mass and to make a preliminary comparison with model and simulation predictions.

(vi) The general conclusion of the efficiency of search for VYG proxies in nearby voids should stimulate modellers to advance simulations in order to include in their results a more detailed characterization of the VYG surroundings.

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