Once in a blue stream

Detection of recent star formation in the NGC 7241 stellar stream with MEGARA

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ABSTRACT

Aims. In this work we aim to study the striking case of a narrow blue stream with a possible globular cluster-like progenitor around the NGC 7241 galaxy and its foreground dwarf companion. We want to figure out if the stream was generated by tidal interaction with NGC 7241 or it first interacted with the foreground dwarf companion and later both fell together towards NGC 7241.

Methods. We use four sets of observations, including a follow-up spectroscopic study of this stream based on data taken with the MEGARA instrument at the 10.4-m Gran Telescopio Canarias using the integral field spectroscopy mode, Mount Lemmon 0.80-meter telescope, Telescopio Nazionale Galileo, DESI imaging Legacy surveys and GALEX archival data. We also use high resolution zoom-in cosmological simulations.

Results. Our data suggest that the compact object we detected in the stream is a foreground Milky Way halo star. Near this compact object we detect emission lines overlapping a less compact, bluer, and fainter blob of the stream that is clearly visible in $g$. Our data suggest that the compact object we detected in the stream is a foreground Milky Way halo star. Near this compact object we detect emission lines overlapping a less compact, bluer, and fainter blob of the stream that is clearly visible in $g$.

Key words. galaxies: interaction – galaxies: formation – galaxies:dwarf – surveys

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1. Introduction

Star formation in the low-z universe mostly occurs inside galactic disks through dynamical instabilities (Kennicutt 1998; Leroy et al. 2008a). These processes dominate the current Star Formation Rate (SFR) in the Universe but are not exclusive. Many authors report observations of star forming regions outside galactic disks (e.g., O’Dea et al. 2004a; Sengupta et al. 2009; Howk et al. 2018a; Smith et al. 2010). In these regions, a gas shell, a gas stream, or a gas cloud suffers a strong perturbation, collapses and generates a new population of stars. Some examples of this process are the star formation clumps observed in boundaries of radio jets and lobes (Graham 1998; Mould et al. 2000; O’Dea et al. 2004a), in clouds of extraplanar gas originated by the galactic fountain (Tüllmann et al. 2003; Howk et al. 2018a), or in highly perturbed regions like the tidal debris left from first interactions during wet major mergers (Sengupta et al. 2009; Hibbard et al. 2005). If massive enough this new self-gravitating stellar population lead to the formation of a young star cluster (Howk et al. 2018b), or, in strong tidal interactions, new objects like Tidal Dwarf Galaxies, TDG (Duc & Mirabel 1998) Duc et al. 2000; Smith et al. 2007; 2010).

Two ingredients are needed in these processes to allow the formation of a new stellar population: the presence of a cold/molecular gas cloud and a strong perturbation. Strong perturbations are present in most galactic systems in many forms, from gas sound waves (e.g., SNe shells or AGN jets) to tidal perturbations by companions or non-axisymmetric structures inside galaxies (Buta et al. 2019). Besides these special conditions, the formation of cold/molecular clouds is not seen outside the disk plane. In the disk outskirts, the dynamics of gas is tightly bounded with the Circum-Galactic Medium (CGM) properties. High-mass galaxies develop a warm-hot CGM that inhibits the formation of cold clouds of molecular gas in hydrostatic equilibrium far from the disk region (Keres et al. 2005). On the other hand, low-mass galactic systems present the prototypical galactic fountain where metal-rich gas is released by SNe winds to the CGM, or even the Inter-Galactic Medium (IGM), and quickly cools down and falls back to the disk from large radii. So, there is a strong dependence on the distribution of extraplanar star formation with galaxy virial mass (i.e., CGM’s virial temperature) (Fraternali 2017). Similarly, it is favored in low-mass systems that cold gas infalling from the IGM through cold flows, or inside gas rich satellites, penetrates down to the galactic disk, and/or condensates inside gas-rich filaments or tidal structures (Fraternali 2017).

The star formation in the tidal tails generated around infalling satellites during gas rich minor mergers has only been studied in a few works using Smoothed-Particles Hydrodynamic (SPH) simulations (Kapferer et al. 2009). Current studies of extraplanar star formation have mainly focused on the consequences of major mergers and interactions within massive clusters of galaxies (Tüllmann et al. 2003; O’Dea et al. 2004b; Leroy et al. 2008b; Werk et al. 2008; McDonald et al. 2012). Furthermore, predictions from the theory of galaxy formation and evolution points towards a relation between the minimum radius reached by gas inside infalling satellites before being ram pressure stripped, and the properties of the gas surrounding the central galaxy (Hester 2006), that are tightly linked with the total mass of the central galaxy (Birnboim & Dekel 2003). If the central galaxy is a low-mass system, i.e., if it has not developed a dense warm-hot CGM, the satellite can reach lower radii before it is totally ram-pressure stripped. In this situation the satellite’s gas can shock with the central galaxy HI (from the galactic fountain or inside the disk) and produce extraplanar star formation (Noreña et al. 2019). In this situation, newborn stars will follow a similar orbit as the infalling galaxy (Lim et al. 2018), and, as a result, we would observe a blue stellar stream.

NGC 7241 is a galaxy that is transitioning from the low-mass, with no warm-hot corona, to the high-mass scenario (like the MW), with a spatially extended HI gas disk (Leaman et al. 2015). The first inspections of this galactic system in the UV images from Galex seemed to show that this edge-on disk galaxy have a strong off-plane star formation, although this galaxy shows no morphological evidence of a recent interaction triggering it. The lack of morphological perturbations was also in contradiction with the HI observations by Giovanelli & Haynes (1984) that showed evidence of the presence of a possible dwarf companion in the field. More recently, Leaman et al. (2015) confirmed the presence of this companion, it is an actively star forming dwarf in the foreground of the NGC 7241 galactic disk. The foreground dwarf hosts the strong off-plane star formation observed in the Galex images. Leaman et al. (2015) also discovered a nearby stellar tidal stream, and, using HeI, they studied the kinematics of all components in the system and concluded that the stream is associated with the star-forming companion. However, the analysis of the connection between the so-called “companion” and the NGC 7241 was not conclusive. The authors also studied the companion’s SFR and observed that it is one order of magnitude higher than expected in a normal galaxy of its mass. These results, in addition to the absence of strong morphology perturbations and of an enhanced SF in the NGC 7241 disk, pointed towards an unknown but potentially complex interaction history. Particularly, it is under study if the infall of a small galactic system towards the companion could create the observed narrow tidal stream.

In this paper, we present follow-up spectroscopic observation of the blue stream of NGC 7241, with the aim of constraining the nature of a compact object found inside the stream. In addition to undertaking a new photometry and structural study of this stream, we explore the formation scenario of this rare blue streams in the nearby Universe using cosmological simulations. In this context, we explore if our observations of a possible star forming progenitor are showing a process similar to the one which shaped the SFH of some dwarfs in the Local Group that show an early star formation peak followed by a fast quenching (Weisz et al. 2015).
Fig. 1. NGC 7241 images including the blue stream and the dwarf companion projected on its center. Upper-left: L-filter wide-field image obtained with the Mount Lemmon 0.80-meter f/7 Ritchey–Chrétien telescope. The total field-of-view is 22.5 × 22.5 arcmin. The red square marks the field of the full color image displayed in the bottom panel. Upper-right: u' -band observations obtained with DOLoRes at the TNG 3.58-meter in La Palma observatory. The purple filled square marks the field of view of the MEGARA IFU field which is placed on the compact object in the stream. Bottom panel: A zoomed, full color version of the deep image obtained with the Mount Lemmon 0.80-meter telescope, including the NGC 7241 central region marked with a red square in the upper left panel.
Pipeline version 0.10.1 (MEGARADRP; see Pascual et al. 2018) and combined to generate the final Row-Stacked-Spectra (RSS hereafter) FITS frame that was used for our analysis.

The data processing included bias subtraction, gain normalization of the two amplifiers, tracing and extraction of the 567 object plus 56 sky fiber spectra, wavelength calibration, flat-fielding correction of the blue-to-red and fiber-to-fiber response and absolute flux calibration. The fiber tracing, extraction modeling and flat-fielding (TraceMap, ModelMap and FiberFLx recipes, respectively) were performed using halogen lamp observations taken at the end of night. The wavelength calibration was performed using observations of the 5 ThAr lamps available at the Instrument Calibration Module (ICM). The standard deviation of our wavelength calibration solution achieved was 0.021 Å for a reciprocal linear dispersion of 0.22 Å pix$^{-1}$. In order to perform absolute calibration of these data the spectrophotometric standard star HR 5501 was also observed during that night and processed using the MEGARADRP. More information on the processing of MEGARA data using the MEGARADRP can be found in García-Vargas et al. (2020).

2.2. Mount Lemmon 0.80-meter imaging observations

We collected deep imaging of the field around NGC 7241 at the Mount Lemmon Sky Center (Steward Observatory, University of Arizona) with an 80 cm aperture f/7 Ritchey–Chrétien telescope. We used a SBIG STX16803 CCD camera was that provided a pixel scale of 0.33′′ pixels$^{-1}$ over a 22.5′ × 22.5′ field of view. We obtained a set of 32 individual 1200 second images with an Astrodon Gen2 Tru-Balance E-series luminance filter (see Sec. 3.2). This emission emanates from a second, fainter over-density just North of the GC-CAND, which is visible in both the FUV channel and 175 seconds in the NUV channel.

3. RESULTS

3.1. Radial velocity from MEGARA observations

The blue stream of NGC 7241 (see Fig. 1) bottom panel) is a ~45° long tail that seems to emanate from a bright compact object (GC-CAND) located at a position angle of ~150 degrees (measured from North to East). The visual inspection of the Row-Stacked Spectrum (RSS hereafter) 2D FITS file created by the MEGARADRP from the observation centered at the GC-CAND (see Sec. 2.1) reveals the presence of two faint emission lines in several spaxels that correspond to Hβ and [O III]λ5007Å at the approximate redshift of NGC 7241 ($z$=0.0048 or 1447±1 km s$^{-1}$; Lu et al. 1993). Since the location of these lines does not coincide with the brightest spaxels in the continuum, we decided to determine the heliocentric radial velocity map in the vicinity of the possible nucleus of the NGC 7241 stream using these data. For that purpose, we made use of the analysis and visualization tools distributed along with the MEGARADRP, namely the analyze$_{rss}$ and visualization codes (see Castillo-Morales et al. 2020). The first code was used to measure the intensity and recession velocity of every emission line detected in any spaxel with a line peak signal-to-noise ratio (S/N) above a given threshold along with the corresponding error.

Interestingly, in our case we found a coherent structure with emission above S/N=5 in 11(5) spaxels in the Hβ ([O III]λ5007Å) line but not at the position of the GC-CAND (see Fig. 1). This emission emanates from a second, fainter overdensity just North of the GC-CAND, which is visible in both the FUV channel and 175 seconds in the NUV channel.

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1 More information on the processing of MEGARA data using the MEGARADRP can be found in García-Vargas et al. (2020).
2 The errors in radial velocity were obtained from the covariance matrix as part of the analysis performed by the lmfit python package included in the MEGARATools with the MEGARADRP using a Levenberg-Marquardt least-squares minimization method.
from the continuum windows used to measure the continuum level and the only this feature is out of the line window but was also excluded from given that it is well separated from our line of interest. Note that not recognition of the radial velocity, line flux or line ratios in STREAM-CORE near Hβ at around 4878 Å. This feature does not a

The only absorption or emission detail visible in the spectrum obtained at the GC-CAND location is at 4857.0 Å, with a significance of about 5–6 sigma (see Fig. 4, bottom panel). Assuming the absorption is Hβ we see that it is blue shifted by −269 km s⁻¹. To determine the radial velocity from this line we needed to increase the S/N that was originally of ~ 2. To do that we reduced the resolution from R ~ 5000 to R ~ 2500 using Gaussian smoothing and rebinned the spectrum to the scale of 2 pix per FWHM. With these operations we achieve a S/N ~ 9. Finally, we fitted the resulting spectrum by the PEGASE.HR stellar population models (Le Borgne et al. 2004) using the NBORS tool (Chilingarian et al. 2007). The resulting radial velocity for the GC-CAND is of \( V_\text{hel} = -233 \pm 33 \text{ km s}^{-1} \) with respect to the solar system barycenter.

### 3.2. Photometry and structural properties

The photometry of the NGC 7241 stream in the DES images was carried out using GNU Astronomy Utilities (Gnuastro)³. All the measurements have been done using Gnuastro’s Make-Catalog tool (Khalighi & Ichikawa 2015; Khalighi 2019). This tool has been developed with emphasis on the detection of low surface brightness, diffuse sources. Surface brightness limit of the images, giving the depth of the image, were calculated following the standard method of Román et al. (2020), i.e. the 3σ measured value on a 100 arcsec² aperture and yield 28.99 [mag arcsec⁻²] for g, 28.42 [mag arcsec⁻²] for r and 28.28 [mag arcsec⁻²] for \( \mu \).

We used NoiseChisel (Gnuastro) to perform sky-subtraction on the DESI images previously processed with the Legacypipe (see Sec. 2.3). For that purpose, the image is tessellated, with tiles having a configurable number of pixels (typically 40x40). The sky background in the tiles with detection will be obtained by interpolation of the signal in the neighbouring tiles with no detection, and then subtracted locally. In this way the environment is of interest. Note that not only this feature is out of the line window but was also excluded from the continuum windows used to measure the continuum level and the continuum rms (needed to compute the errors in the line flux)

³ We have found that the feature resembling a P-Cygni absorption component is due to the presence of a sky subtraction residuals that can be seen in the original high-resolution spectrum of STREAM-CORE near Hbeta at around 4878 Å. This feature does not affect the determination of the radial velocity, line flux or line rations in STREAM-CORE given that it is well separated from our line of interest. Note that not only this feature is out of the line window but was also excluded from the continuum windows used to measure the continuum level and the continuum rms (needed to compute the errors in the line flux)

⁴ http://www.gnu.org/software/gnuastro
Photometry of the stream was also obtained in the u'-band using the TNG data of NGC 7241 described in Sec. 2.2 and the same elliptical aperture and masking as for the bands g and r. To find the zeropoint of the u-band image (30.18 ± 0.04 mag), matched aperture photometry was used in comparison with Sloan Digital Sky Survey (SDSS) images. With that purpose, we ran NoiseCusel and Segment and selected "Clumps" with S/N > 10 and axis-ratio > 0.85 in the u-band image. An aperture of radius 2 arcsec was then placed over them in the TNG and SDSS images (using MakeProfiles) and the photometry over the apertures obtained with MakeCatalog. The zeropoint was estimated by calculating the difference (for stars with magnitude between 17 to 20).

The u'-band photometry is also included in Tab. 1 and discussed in Sec. 3.3. Finally, the width of the stellar stream has been estimated for three points along the stream (maximum, minimum and intermediate width) assuming a distance of 22.5 kpc. The results are given in Tab. 2.

Despite the low exposure times of the GALEX images, the emission from the stellar stream is also detected in both bands due certainly to its very blue color. Using circular apertures of 15 arcsec (~3 times the FWHM of the GALEX PSF) in radius centered on RA(J000) = 22:15:52.38 and Dec(J2000) = 19:11:29.3 we estimated FUV and NUV aperture magnitudes of 20.10 mag and 20.06 mag with estimated errors between 0.05-0.11 mag and 0.16-0.22 mag, respectively. The FUV-NUV color inferred is (FUV-NUV)=0.045 with an error no lower than 0.18 mag. The UV photometry was performed as in Gil de Paz et al. (2007), so it takes into account the highly Poissonian regime of the GALEX AIS images and the potential presence of low-frequency background variations. The blue color found corresponds to a roughly flat $f_λ$ spectrum that is comparable to that measured in star-forming dwarfs and the outermost regions of spiral disks (see Bouquín et al. 2018), including Extended Ultra-Violet disks (XUV-disk), and it is commonly associated with regions of active recent star formation and low dust content.

3.3. Metallicity

We estimate the metal abundance of the ISM in the stream of NGC 7241 using the two emission lines clearly detected in our optical spectra, namely [O iii] $\lambda$5007 Å and Hβ. The best-fitting gaussians to each of these two lines after adding the spec-

Fig. 3. Upper panel: Image cutout obtained from the DESI Legacy surveys data with LEGACYPIPE centered in the compact object GC-CAND (marked with two red lines) embedded in the NGC 7241 stream and classified as a foreground halo star in our study (see Sec. 4.2). The total field-of-view of this image is $5 \times 5$ arcmin. The orange square indicates the extend of the figure shown in the bottom panel. Bottom panel: The apertures used to perform the photometry of the stream (dashed blue line) and its possible progenitor STREAM-CORE (red circle) are overlapped in a r-band DESI LS image of the stream. The source GC-CAND (marked with a black circle encompassed in two red lines) was also masked for deriving the results given in Tab. 2.

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tra of the 11 spaxels where line emission is clearly detected (S/N ≥ 5 at the peak of the line) yield [O\textsc{iii}]λ5007/\Hβ line ratio of −0.23^{+0.14}_{-0.21}. Alternatively, the direct sums of the fluxes above the continuum in the (rest-frame) range between 4855 Å and 4867 Å yield a ratio of −0.09^{+0.16}_{-0.20}. Based exclusively on this single-line ratio we cannot obtain too much information about the ionization properties in the possible progenitor of the stream STREAM-CORE (either on the conditions of the gas or the ionizing spectrum). This line ratio, according to the typical ones measured in HII regions in the normal galaxies included in the CALIFA sample (see top-left panel in Figure 7 of Morisset et al. 2016), favors an Oxygen abundance most likely in the range 8.35 < 12 + log(O/H) < 8.55 (see their colorbar), or between 0.4xZ⊙ and 0.63xZ⊙ (adopting a solar oxygen abundance value of logA(O)=8.75; Bergemann et al. 2021).

4. Discussion

4.1. The NGC 7241 and its dwarf companion

In agreement with the footprints of an NGC 7241 companion in the HI distribution (Giovanelli & Haynes 1984) and the final confirmation by Leaman et al. (2015), we show that the dwarf irregular that overlapps the main body of NGC 7241 is clearly visible in the Mount Lemmon 0.80-meter deep image (Fig. 1 bottom panel). We named this new system DWARF-COMPANION, hereafter.

For the superimposed DWARF-COMPANION object (see Fig. 1 top-right panel) in Leaman et al. (2015) the authors estimate a $M_r \sim 1.5 \times 10^8 M_\odot$, also obtained from SED fitting. Though very uncertain, the size and Hα velocity dispersion of the DWARF-COMPANION imply a dynamical mass of order $\sim 10^9 M_\odot$, so this would be a baryon dominated object.

Using this data on the total mass of each galactic system, in the following sections we will focus on the origin and properties of the blue stream detected in the NGC 7241 and its dwarf companion’s neighbourhood.

4.2. Who is the progenitor of the blue stellar stream?

As mentioned in Sec. 3.1 the blue stream around NGC 7241 seems to emanate from a bright compact object we named GC-CAND, that is close to another bright but fainter structure we called STREAM-CORE. In this section we study which of these two objects is the best candidate to be the stream’s progenitor.

GC-CAND (R.A.=22:15:52.4 Dec.=+19:11:32.9) is an object that was also catalogued in the Gaia early DR3 (Gaia Collaboration et al. 2021). It has a Gaia G magnitude of G=20.2 with the assumed distance comes out to absolute G magnitude of $M_G = -11.5$ which roughly corresponds to $M_V = -11$. This absolute magnitude places this source in the very bright end of Globular Clusters ($M_V < -10$) where we know that more than 50% of sources are the relic nuclear star cluster of the galaxy that is being stripped (Voggel et al. 2019). Streams with such embedded former nuclei have been discovered in other galaxies (e.g. Jennings et al. 2015). GC-CAND also has a larger Gaia BP-RP excess factors similar to what is seen for GCs/Nuclei in nearby galaxies (Voggel et al. 2020). Gaia proper motions have large errors at these faint magnitudes and its proper motion in RA direction is detected at 2.5 σ level, which is not significant enough to clearly mark it as foreground star. Therefore, in order to confirm whether the GC-CAND compact object is associated to the stream, a radial velocity measurement is required. In Sec. 3.1 we show that we obtain a velocity of $V_\text{hel} = -233 \pm 33$ km s$^{-1}$ with respect to the solar system barycenter, therefore, this compact object is not associated with NGC 7241 that has a systemic velocity of about 1500 km s$^{-1}$ but an accidental foreground Milky Way star. To explore this further, we make a simple estimate of the velocity range expected in this line-of-sight using the SDSS DR16 spectra archive (Ahumada et al. 2020). Within a 30 arcmin cone around the object, there are ∼ 50 stars with observed SDSS spectra. Their heliocentric velocities range from −560 to +125 with a median value of −54 and a standard deviation of 89 km s$^{-1}$, estimated by the median absolute deviation. The star velocity distribution shows the second peak near −200 km s$^{-1}$ and 8 of 50 stars have velocity less than −230 km s$^{-1}$. Thus, we conclude that GC-CAND has a radial velocity which is typical for Galactic halo stars and cannot be the core of this stellar stream.

The second bright source we detected close to the stream’s geometrical center is the STREAM-CORE. From our broad-band photometry (see Tab. 1) we obtained that it would have an absolute magnitude of $M_V \sim -10$ at the distance of NGC 7241. We also find that its color is bluer than that of the stream, as expected from the emission only observed in this region in the MEGARA spectra (see discussion in Sec. 3.1 and Fig. 2 center panel). In Sec. 3.1 we showed that the systemic radial velocity of STREAM-CORE region is 1547.92±1.65 km s$^{-1}$ (from Hα in emission), this value is similar to the one of both, the NGC 7241 and its DWARF-COMPANION, so it is not a strong statement to assume that the STREAM-CORE is somehow related with those systems. In addition, the shape of the stream around the position of the STREAM-CORE (see Fig. 2 upper panel) resembles the typical structure of a tidally stripped dwarf galaxy (see e.g., Wang et al. 2023). Its location in the geometrical center of the stream, radial velocity, color, and shape allows us to conclude that this over-density is likely the actual progenitor of the stream, which is undergoing a current episode of induced star formation by the tidal interaction with the NGC 7241 or its foreground dwarf companion. Obviously, the presence of gas in the progenitor of the stream is essential to form new stars, this suggest STREAM-CORE cannot be a typical globular cluster, since those have no gas, but probably the main body of an accreted dwarf satellite.

| Source   | area [pixels] | area [as²] | $m_g$  | $m_r$  | $m_V$ | $<μ_g>$ | $<μ_r>$ | $<μ_V>$ | $<g-r>$ | stream [mag] | TOTAL [mag] |
|----------|--------------|------------|--------|--------|-------|---------|---------|---------|---------|-------------|-------------|
| STREAM   | 7037         | 483.05     | 19.23±0.01 | 19.07±0.02 | 18.11±0.005 | 25.94  | 25.78  | 24.82  | 0.16±0.03 |             |             |
| CORE     | 166          | 11.39      | 22.21±0.05 | 22.13±0.06 | 22.22±0.03 | 24.85  | 24.77  | 24.23  | 0.08±0.11 |             |             |
| TOTAL    | 7203         | 494.44     | 19.16±0.01 | 19.01±0.02 | 18.07±0.005 | 25.90  | 25.74  | 24.80  | 0.15±0.03 |             |             |

Table 1. Photometry results for the NGC 7241 stream from Gnuastro. We include the data from the stream, the structure we labeled STREAM-CORE, and the combined (TOTAL).
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Fig. 4. Top panel: MEGARA LR-B spectrum of the North-West region showing line emission (see top-right region of panel b in Fig. 2) fitted by a multi-Gaussian for emission lines with an additive polynomial for continuum. The Hβ line and the [O III] λλ 4959, 5007 Å doublet are identified along with their position for a redshift z = 0.00515. Bottom panel: The spectrum of the compact source embedded in the stream fitted by the PEGASE.HR stellar population models using the NBcorrs program. The black line represents the smoothed spectrum of the object and the red line corresponds to the fit. The blue lines and green dots show the flux errors and the data residuals (shifted to -0.1 for top panel).

Table 2. Minimum, maximum and median estimations of the NGC 7241’s stellar stream on-sky width measurements. We include an estimation of its physical width assuming a distance to the stream of 22.4 Mpc [Leaman et al., 2015].

| RA (deg) | DEC (deg) | Width (arcsec) | Width (kpc) |
|---------|----------|----------------|-------------|
| Max.    | 333.97123 | 19.18.6971     | 11.960      | 0.80        |
| Min.    | 333.96934 | 19.190611      | 7.372       | 1.30        |
| Med.    | 333.97307 | 19.183051      | 8.798       | 0.95        |

4.3. Properties of the blue stream’s progenitor

In order to better understand the NGC 7241 stream, we can make a quantitative estimate of which should have been the NGC 7241 stream progenitor’s mass using the results of Johnston et al. (2001) and Erkal et al. (2016) who derived mass estimates for stream progenitors assuming that the stream plane is viewed face-on or edge-on, respectively. These estimates work by determining how the orbits of stars in a given potential fan out once they are ejected from the progenitor and connecting this to the progenitor’s dynamical mass.

First we will make the computations assuming that the stream is associated with the central galaxy, not with the dwarf and is seen face-on. Assuming that the stream is on a circular orbit at 20 kpc and that the circular velocity at this radius using the mass estimations in Sec. 4.1 is 202 km s⁻¹, we can use Eq. 12 in Johnston et al. (2001) to obtain that the progenitor mass of the stream is between 1.3 – 5.5 × 10⁷ M⊙ using the minimal and maximal width of the stream (see Tab. 2), respectively. We note that this mass estimate is linearly proportional to the stream’s pericenter and thus the progenitor mass could be substantially lower if the stream is on an eccentric orbit at apocenter at present day. Alternatively, if we now assume that we are observing the stream edge-on, we can use the results of Erkal et al. (2016) (Eq. 23) and we obtain a progenitor mass of 6.2 × 10⁷ – 2.7 × 10⁸ M⊙ for the minimal and maximum stream width (Tab. 2), respectively. We note that these mass estimates are much lower than for a stream with the same width in the Milky Way since NGC 7241 is a much less massive galaxy, which yields a larger tidal radius (i.e., width) for the
stream presented in this work. Similarly, we can obtain the progenitor’s mass assuming that the stream is linked to the dwarf-companion and not to the central galaxy. Using the Johnstion et al. (2001) approach (its Eq. 12) and the dwarf-companion mass estimations obtained in Sec. 4.1, we find that the progenitor mass of the stream should be as low as $3.2 \times 10^4 - 1.4 \times 10^5 M_\odot$.

We note that these estimates suggest that if the stream is on a near circular orbit around NGC 7241, its progenitor is likely a dwarf galaxy stream. Otherwise, if it is on a very radial orbit pointing towards NGC 7241, or it is orbiting the dwarf-companion, then it could come from a lower mass system like a globular cluster.

Interestingly, the stream width increases with projected distance from NGC 7241/dwarf-companion (see e.g., Fig. 1). If the stream is on a very eccentric orbit, this may be due to the characteristic shell-like debris which causes the stream width to increase with radius (e.g. see Fig. 8 of Hendel & Johnston 2015). Alternatively, if there is a strong distance gradient along the stream, where the parts of the stream that are closest to the center of NGC 7241/dwarf-companion in projection is in fact farthest away from us in 3D, it is possible that the most distant debris is too diffuse to observe. The change in the apparent width of the stream could, in that case, merely be an observational effect. If the stream plane is instead being viewed close to edge-on, the change in the stream width could be due to an overlap with different parts of the stream along the line of sight. The specific viewing angle can have a large impact on how we interpret tidal debris (e.g., Barnes & Hibbard 2009), and can lead to apparent asymmetric observations of intrinsically symmetric tidal features. Lastly, the stream could physically be asymmetric in nature. Recent data from the Milky Way have revealed that several stellar streams are asymmetric (e.g., Jelum: Bonaca et al. 2019 and Pal 5: Bernard et al. 2016; Bonaca et al. 2020). Asymmetric stellar streams can be produced through various mechanisms such as interactions with galactic bars (Price-Whelan et al. 2016b; Erkal et al. 2017; Pearson et al. 2017), heating of parts of the streams due to interactions with dark substructure (e.g., Johnston et al. 2002; Ibata et al. 2002; Bonaca et al. 2014), interactions with nearby systems, or specific orbit families within the parent potential causing parts of the stream to “fan” out (e.g., Pearson et al. 2017; Fardal et al. 2015; Price-Whelan et al. 2016a; Yavetz et al. 2015). It is unclear from the edge-on view of NGC 7241 whether the galaxy hosts a bar, as we do not observe any evidence of an x-shaped central structure typically found in barred spirals (e.g., Bureau et al. 2006), but it is clear that the stream could be perturbed by the presence of the second object in the system. NGC 7241 or dwarf-companion. Additionally, if interaction with the bar was the cause, the stream would have already needed to have a close pass with the center of NGC 7241 but no evidences of such interaction are present in the system. Deeper data in the future will hopefully allow us to distinguish between the possible scenarios discussed in this section.

4.4. Is NGC 7241 the host galaxy of the blue stellar stream?

With the mass estimations presented in Sec. 4.1, in hand, if the stellar stream has been generated by the tidal interaction with NGC 7241 and has a mass of $M_{\text{stream}} \sim 2 \times 10^5 M_\odot$ (Sec. 4.3), then its tidal radius would be $R_{\text{tid}} \sim 823$ pc or $\sim 8'$. Conversely, the tidal radius for the object with respect to the potential of the baryon dominated dwarf-companion with a mass $M_{\text{stream}} \sim 1 \times 10^5 M_\odot$ would be $R_{\text{tid}} \sim 600$ pc or $\sim 6'$. In the previous sections we showed that the width of the stream ranges from 800 pc to 1.3 kpc. These values are larger than the tidal radii crudely estimated from the mass profile and projected distance of NGC 7241, and also than the one derived from the companion dwarfs’ mass, so it would seem sensible to assume that the disrupting system can be dominated by either the tidal influences from the potential of NGC 7241, or that from the dwarf galaxy companion alone. This result is highly sensitive on the original mass of the stream’s progenitor, a value that is highly uncertain (see Sec. 4.3) so we can not use this argument alone to reach any conclusion.

Is there any other evidence that supports the hypothesis that the stream have been bound to the SMC-like companion dwarf (dwarf-companion) prior to falling into NGC 7241? The apparently young dynamical age of the stream (see Section 6.4 in Leaman et al. 2015), and the similar velocity offset ($\sim 190$ km/s; Leaman et al. 2015) of the stream and dwarf-companion with respect to the NGC 7241 would seem to favour this scenario. Additionally, if the dwarf irregular satellite is undergoing a relatively recent infall towards the NGC 7241 (see further discussion in Sec. 4.5) and thus it still keeps its own substructure (the stream) it may explain why it and the central galaxy seem to show signatures of a recent star formation burst. Whether or not it is expected that an SMC-mass system like the dwarf-companion has a companion dwarf of the mass of the stream progenitor is discussed further in Sec. 4.5.

In conclusion, with the current data, we can not confirm that the stream is associated with the dwarf companion, although none of the analysis presented here disfavours this hypothesis.

4.5. The origin of blue streams: insights from theory, simulations and observations of the local group dwarf’s SFH

Star-formation is rarely detected in stellar streams, as it requires the presence of dense molecular clouds that would be quickly heated up and destroyed by the many processes involved in the satellite-central galaxy interaction (e.g., Emerick et al. 2016; Cortese et al. 2021). As a consequence, most tidal streams in the local universe host old stars that were stripped out from its progenitor’s dwarf galaxy by a minor merger event. However, this scenario does not apply to all dwarf-central galaxy interactions. From the theory of galaxy formation and evolution we expect that changes on the mass of the central galaxy modify the efficiency that the gas ram pressure stripping process has on removing gas from the incoming satellites (Koutroumi & Catenio 2019). These changes probably occurred in the Milky Way – Andromeda galactic systems when transiting from a low-mass system with no warm-hot corona to the current situation with a well defined warm-hot CGM.

In the early scenario where dwarf galaxies merged with a low-mass MW with no well developed warm-hot CGM, the infalling satellites were able to keep their gas for a long time, and thus, we expect they could suffer a strong star formation burst (Di Cintio et al. 2021) similar to the one observed in the NGC 7241’s companion, or in observations of similar interacting systems (e.g., Kapferer et al. 2009; Beaton et al. 2014). This star formation peak would be clearly reflected in their SFH. Many authors obtained the SFH of the local group dwarfs by fitting the color-magnitude diagrams to evolutionary models and reported an SFH with a single peak (Aparicio & Hidalgo 2009; Weisz et al. 2014), and obtained results that may be consistent with the aforementioned hypothesis and with what is currently occurring in the NGC 7241 system. However the exact shape of the SFH...
of these objects is difficult to estimate as it depends on multiple
variables, for example, more massive and concentrated satellites
are more efficient on shielding gas in their central regions from
the ram pressure stripping, so they can keep forming stars for
longer times (Cortese et al. 2021; Font et al. 2022). Although
this degeneracy is present, a gas rich dwarf galaxy will always
suffer a strong star formation burst in its first interaction with
the central galaxy due to compression of molecular clouds
induced by tidal forces (Di Cintio et al. 2021). In this scenario
it is expected that the gas clouds and stars in the star forming
complexes generated as a consequence of the interaction will
be affected by the tidal forces from the central system and
will became part of the resulting tidal streams. Therefore,
this new stream, at least in the first orbit, will include young stars
and gas that has not been yet completely stripped out from the
progenitor, i.e., will be a show up as a blue stream.
Recent zoom-in cosmological simulations captured this process
at high-z for z=0 MW-mass systems, i.e., when these were
low-mass enough, showing the formation of blue streams
(Roca-Fàbrega et al. 2016; Buck et al. 2019). An example is the GARROTXA model (Roca-Fàbrega et al. 2016), a
high-resolution simulation of the formation of an MW-mass
galactic system. In this model, we detected that at $z \sim 1.0 - 1.5$,
that is when the progenitor has a mass of $\sim 10^{11} M_\odot$, satellites
almost reach the galactic disk region without losing their cold
gas (see Fig. 5 bottom panels). We also observe ongoing strong
star formation inside the satellite’s core and also on the stripped
stellar stream, i.e., we observe the formation of a blue stream
(see Fig. 5 top panels). Interestingly, satellites contain almost no
stars previous to their interaction with the MW-mass progenitor,
therefore this interaction induces the first strong star formation
episode within them. In this same model we also observed that
at $z=0$, i.e. when the MW-mass system already developed a
warm-hot gas corona (Roca-Fàbrega et al. 2016), satellites with
a similar initial mass and gas content cannot retain their cold
gas and show no star formation in the tidal streams.
These results suggest that in the observed blue stream we may
be watching a tidally induced star formation burst equivalent
to the one that shaped the SFH of some of the dwarf galactic
systems in the Local Group (Weisz et al. 2015; Di Cintio et al.
2021) when the MW and Andromeda were low mass galaxies.

Before finishing the discussion section we want to em-
phasise that we cannot discard the possibility the blue stream
is associated with the star-forming dwarf galaxy (DWARF-
COMPANION), not with the NGC 7241 itself. In recent years
there has been a growing interest in detecting the presence
of streams around low-mass galactic systems, i.e., LMC and SMC-
like galaxies (e.g., Martínez-Delgado et al. 2012; Kado-Fong
et al. 2020). The ΛCDM theory of a hierarchical universe pre-
dicts the presence of very low-mass halos interacting with dwarf
galaxies in low-density environments (e.g., Guo et al. 2011;
Sales et al. 2013). Some examples of these interactions were re-

Fig. 5. Blue streams in the GARROTXA cosmological simulation of a z=0 MW-mass galaxy, observed at z=1.5. Top panels: Total stellar surface luminosity. Bottom panels: Projected cold gas density ($T < 5 \times 10^4 \text{ K}$), green-yellow are high-density gas regions, blue-black are low-density. Cyan dots (left) and black dots (right) show the position of the star particles younger than 350 Myr.
ently discovered by the MADCASH Survey [Carlin et al. 2016, 2019]. In this context, we propose an alternative scenario: a small galactic system interacted with the DWARF-COMPANION inducing the observed star formation burst and generating the observed blue stream. Later, both of them fell simultaneously towards the NGC 7241. Metallicity estimations for each one of the components in the system could help to unveil which is the true scenario. However, the oxygen abundances we obtained here are too uncertain to allow us to confirm or discard any hypothesis. So, we conclude that more observations are needed to unveil the real scenario posed by this complex galactic system.

5. Conclusions

In this paper, we have characterized the structure of the blue star-forming stream of NGC 7241 discovered by [Leaman et al. 2015] and the kinematics of its most plausible progenitor (STREAM-CORE) using new available images in different broad-bands from four independent sources. In order to explore if this stream had a globular cluster-like progenitor, we obtained follow-up observations using the MEGARA instrument at the GTC in its IFU configuration.

We concluded that the bright compact object (GC-CAND) embedded in the stream that we initially considered as the most probable progenitor is actually a foreground halo star overlapping the path of the stream. However, we report the discovery of a fainter blob in the stream displaying emission lines (STREAM-CORE) which could be interpreted as the actual progenitor displaying a burst of star formation. Our photometric study suggests that this on-going star formation region detected within the stream produces a near-UV luminosity comparable with those observed in star-forming dwarfs and the outermost regions of spiral disks. We also measured the width of the stream and obtained values in the range of the observed tidal streams around the Milky Way. Based on these width estimate, we constrain that the progenitor’s mass, if the stream was created by tidal interaction with NGC 7241, is between $6.4 \times 10^9 \, M_\odot$ and $2.7 \times 10^9 \, M_\odot$ when assuming the in-fall was in a circular orbit. For a more radial orbit, of if it was created by tidal interaction with the (DWARF-COMPANION) this estimate would result in a much lower mass even compatible with the one of a massive globular cluster. Although deeper data is needed to distinguish between these possibilities, the NGC 7241 stream is the stream with the lowest mass progenitor reported so far, providing a lower limit to the detection of narrow stellar streams beyond the Local Group (see also [Pearson et al. 2019, 2022]).

Blue star-forming streams like that observed around NGC 7241 should be a common occurrence around galaxies of similar mass. The current galaxy formation and evolution theories predict the presence of these structures around disk galaxies with stellar masses below or around $10^{10.5} \, M_\odot$ whose have not developed a warm-hot CGM and, therefore, the merging dwarf galaxies can keep their gas for longer times. We show that these structures are also commonly observed in high-resolution cosmological simulations of galactic systems with similar mass as NGC 7241. This scenario also agrees well with the tidal interaction and ram pressure stripping processes that produced the observed bursty star formation history on some of the local group dwarf galaxies followed by a fast quenching (e.g., [Kapferer et al. 2009]; Di Cintio et al. 2021) when they first entered the virial radius of Andromeda and the MW progenitors (Aparicio & Hidalgo 2009; Weisz et al. 2014).

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Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

References

Abbott, T. M. C., Abdalla, F. B., Allam, S., et al. 2018, ApJS, 239, 18

Ahumada, R., Prieto, C. A., Almeida, A., et al. 2020, ApJS, 249, 3

Ahlgren, M. 2019, in Astronomical Society of the Pacific Conference Series, Vol. 521, Astronomical Data Analysis Software and Systems XXVI, ed. M. Molinaro, K. Shortridge, & F. Pasian, 299

Ahlgren, M. & Ichikawa, T. 2015, ApJS, 220, 1

Aparicio, A. & Hidalgo, S. L. 2009, AJ, 138, 558

Barnes, J. E. & Hibbard, J. E. 2009, AJ, 137, 3071

Beaton, R. L., Martínez-Delgado, D., Majewski, S. R., et al. 2014, ApJ, 790, 117

Bergemann, M., Hoppe, R., Semenova, E., et al. 2021, MNRAS, 508, 2236

Bernard, E. J., Ferguson, A. M. N., Schlafly, E. F., et al. 2016, MNRAS, 463, 1759

Birnboim, Y. & Dekel, A. 2003, MNRAS, 345, 349

Bonaca, A., Conroy, C., Price-Whelan, A. M., & Hogg, D. W. 2019, ApJ, 881, L37

Bonaca, A., Geha, M., Küpper, A. H. W., et al. 2014, ApJ, 795, 94

Bonaca, A., Pearson, S., Price-Whelan, A. M., et al. 2020, ApJ, 889, 70

Bouquín, A. Y. K., Gil de Paz, A., Muñoz-Mateos, J. C., et al. 2018, ApJS, 234, 18

Buck, T., Macciò, A. V., Dutton, A. A., Obreja, A., & Frings, J. 2019, MNRAS, 483, 1314

Bureau, M., Aronica, G., Athanassoula, E., et al. 2006, MNRAS, 370, 753

Buta, R. J., Verdes-Montenegro, L., Damas-Segovia, A., et al. 2019, MNRAS, 488, 2175

Carlin, J. L., Garling, C. T., Peter, A. H. G., et al. 2019, ApJ, 886, 109

Carlin, J. L., Sand, D. J., Price, P., et al. 2016, ApJ, 828, L5

Castillo-Morales, A., S., P., & Gil de Paz, A. 2020, MEGARA Data Reduction Cookbook

Chilingarian, I., Prugniel, P., Sil’Chenko, O., & Koleva, M. 2007, in Proceedings of the International Astronomical Union, Vol. 241, Stellar Populations as Building Blocks of Galaxies, ed. A. Vazdekis & R. Peletier, 175–176

Cortese, L., Catinella, B., & Smith, R. 2021, PASA, 38, e035

Dark Energy Survey Collaboration, Abbott, T., Abdalla, F. B., et al. 2016, MNRAS, 460, 1270

Dey, A., Schlegel, D. J., Lang, D., et al. 2019, AJ, 157, 168

Di Cintio, A., Mostaghimi, R., Knebe, A., & Navarro, J. F. 2021, MNRAS, 506, 531

Duc, P. A., Brinks, E., Springel, V., et al. 2000, AJ, 120, 1238

Duc, P. A. & Mirabel, I. F. 1998, A&A, 333, 313

Emerick, A., Mac Low, M.-M., Gruenich, J., & Gatto, A. 2016, ApJ, 826, 148

Erkal, D., Kopysov, S. E., & Belokurov, V. 2017, MNRAS, 470, 60

Erkal, D., Sanders, J. L., & Belokurov, V. 2016, MNRAS, 461, 1590

Fardal, M. A., Huang, S., & Weinberg, M. D. 2015, MNRAS, 452, 301

Faucher-Giguère, C.-A. 2020, MNRAS, 493, 1614

Font, A. S., McCarthy, I. G., Belokurov, V., Brown, S. T., & Stafford, S. G. 2022, MNRAS, 511, 1544

Fraternali, F. 2017, Gas Accretion via Condensation and Formation of Spins, ed. A. Fox & R. Davé, Vol. 430, 323

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1

García-Vargas, M. L., Carrasco, E., Mollá, M., et al. 2020, MNRAS, 493, 871
