NGC 2366: An optical search for possible supernova remnants

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Abstract

The results of an optical search for supernova remnants (SNRs) in the nearby irregular galaxy NGC 2366 are presented. We took interference filter images and collected spectral data in three epochs with the f/7.7 1.5 m Russian Turkish Telescope (RTT150) at TÜBİTAK National Observatory (TUG) located in Antalya, Turkey. The continuum-subtracted Hα and continuum-subtracted [Sii]λλ6716, 6731 images and their ratios were used for the identification of SNRs. With [Sii]/Hα ≥ 0.4 criteria, four possible SNR candidates were identified in NGC 2366 with [Sii]/Hα ratios of ~(0.68, 0.57, 0.55 and 0.75), Hα intensities of ~(2.10, 0.36, 0.14, 0.11)×10^{-15} erg cm^{-2} s^{-1} [Sii]λ6716/λ6731 average flux ratios of ~(1.01 and 1.04), electron densities of Ne ~(582 and 513) cm^{-3} and [O iii] λ5007/Hβ λ4861 ~(3.6 and 2.6) line ratio values are obtained for two of the SNR candidates. A shock velocity Vs of 80 ≤ Vs ≤ 100 km s^{-1} is reported. The spectral parameters are obtained for the first time for these possible SNR candidates. The locations of the four SNRs obtained here are found to be consistent with optical and radio results reported so far. One of the sources categorised earlier by XMM-Newton observations as an extended X-ray source position is found to be consistent with one of four possible SNR

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1. Introduction

Supernova explosions and their final dispersion of ejected material have the effect of supplementing the interstellar medium (ISM) with the material produced in stellar interiors and therefore supernova remnants (SNRs) are important for many of the theories of the ISM. Due to the strong photoionisation flux of the central hot star or stars, sulfur is in the form of $S^{++}$ in $\text{H} \text{II}$ regions, where the $\text{[S II]}/\text{H} \alpha$ ratio is typically $\approx 0.1 - 0.3$. Outside an $\text{H} \text{II}$ region, there are not sufficient energetic free electrons to excite $S^+$ and to give rise to the forbidden-line ($\text{[S II]}\lambda 6716, 6731$) emission. Almost all discrete emission nebulae outside $\text{H} \text{II}$ regions showing $\text{[S II]}$-emission are shock-heated and they are probably SNRs and are characterized by $\text{[S II]}/\text{H} \alpha \geq 0.4$.

Several early studies discussed the reasons and importance of searching SNRs in nearby galaxies [see e.g. 37, 44, 45] and in our Galaxy [see e.g. 38, 16, 17]. Although there are a large number of Galactic SNRs, the interstellar extinction and uncertain distances cause selection effects. However, in extragalactic samples, these difficulties are much less. All the SNRs in a galaxy are at the same distance from us. Assuming that we know the distance of this galaxy, the properties of these SNRs can be compared directly. In addition, in an extragalactic survey the foreground extinction is generally low such that the relative positions of SNR samples can be determined precisely. The distributions of the SNRs relative to the $\text{H} \text{II}$ regions in the spiral arms of the Galaxy are calculated using the location of SNRs. Possible SNR progenitors have been searched from these distributions as indicated by Matonick and Fesen [37] and Blair and Long [1]. Extragalactic searches for SNRs were first carried out for the Magellanic Clouds by Mathewson and Clarke [34]. They were the first to use the $\text{[S II]}/\text{H} \alpha$ emission line ratios for optical identification of SNRs. Blair et al. [3], Smith
et al. [55], Blair and Long [11, 12], Sonbas et al. [57, 58] and Leonidaki et al. [32] have already discussed the motivation for observing SNRs in nearby galaxies based on the same emission-line ratio criterion. Radio searches for extragalactic SNRs have been conducted by Lacey et al. [30], Lacey and Duric [29], Hyman et al. [23]. SNR surveys have also been carried out at optical, radio, and X-ray wavelengths by Pannuti et al. [44, 45, 46].

In this work, we searched for SNRs in the nearby dwarf, irregular galaxy NGC 2366 using the criterion $[\text{S}\text{II}]/H\alpha$ ratio $\geq 0.4$. It is described as a “cometary” galaxy by Loose and Thuan [33]. Karachentseva et al. [26] reported its distance to be $D=3.44$ Mpc, which is consistent with Tikhonov et al. [63] who reported $D=3.4$ Mpc. The optical and radio studies by Kennicutt et al. [27] showed evidence of very large H$\text{II}$ regions in NGC 2366. From the emission-line spectrum of this galaxy, it was found to be exceptional due to its excessively high degree of excitation together with a very low reddening. The authors attributed these features to a very low metal abundance, suggesting the existence of an exceptionally energetic source of ionization. Its 21 cm distinctive spectrum and large scale H$\text{II}$ regions are reminiscent of the more distant narrow-lined Markarian galaxies and isolated extragalactic H$\text{II}$ regions. Yang et al. [66] have detected 5 H$\alpha$ sources with broad velocity profiles compared to those of their surrounding H$\text{I}$ regions. This galaxy is also classified as a dwarf blue galaxy, showing indications of spiral arm structure at several wavelengths [10]. It is dominated in H$\alpha$ by the huge extragalactic H$\text{II}$ region in its south west part as indicated by Chu and Kennicutt [8]. Thuan and Izotov [61] provided its V and I photometric results by resolving stars with Wide Field Planetary Camera 2 images obtained from the Hubble Space Telescope (HST). Their 23.65 magnitude limit of the red giant branch stars with ages of $\geq 1$ Gyr provided another distance estimate of $3.42 \pm 0.15$ Mpc which shows a good agreement with the aforementioned values. Early abundance measurements have been reported for this galaxy by several studies [34, 18, 40]. Roy et al. [31, 52] suggested the existence of an expanding supernova bubble in NGC 2363 which is, in fact, a giant H$\text{II}$ region within NGC 2366. Its early radio observations were reported by Kennicutt et al.
at $\lambda 6.3$ and $\lambda 2.8$ cm. The authors measured the whole galaxy (in low resolution) and obtained $10 \pm 1$ mJy flux at 6.3 cm. Their measurement of only the giant H\textsc{ii} region at 2 $''$ resolution yielded $8.5 \pm 0.28$ mJy flux at $\lambda 6.3$ cm. The difference reported in their spectral indices between the entire galaxy and the giant H\textsc{ii} region was attributed to the probable dominant thermal emission across the galaxy. Also Chomiuk and Wilcots \cite{7} reported radio emission of NGC 2366 from VLA continuum data. They diagnosed a number of discrete sources and categorized them as possible SNRs, H\textsc{ii} regions, and/or background radio galaxies. Their findings were in good agreement with various studies and with four SNR candidates in NGC 2366 we report here (see our Fig. 1).

Use of the multiwavelength observations is a great help when trying to understand the characteristics and physical parameters of SNRs as has been pointed out by various studies \cite{37, 31, 62}.

In the earliest photometric studies, NGC 2366 is described as a nearby galaxy with intense and rare star forming bursts characteristic for evolution of late-type dwarf galaxies \cite{53}. Jaskot and Oey \cite{25} and Micheva et al. \cite{39} also reported this galaxy in their study of the most extreme so-called Green Peas galaxies with the highest [O\textsc{iii}]/[O\textsc{ii}] ratios. Their [O\textsc{iii}]$\lambda\lambda 5007, 4959$/[O\textsc{ii}]$\lambda 4363$ ratios yielded electron temperatures of $T_e \sim 15\,000$ K while their [S\textsc{ii}]$\lambda\lambda 6716/6731$ ratios provided electron densities of $N_e = 100$–1000 cm$^{-3}$ in NGC 2366. $T_e \sim 15\,000$ K was reported for nebular emission by several authors \cite{18, 56}. Gonzalez-Delgado et al. \cite{18} also reported an electron density of $N_e = 235 \pm 41$ cm$^{-3}$.

Recently, Vu\v{c}eti\v{c} et al. \cite{65} reported their photometric observational results for NGC 2366 and suggested the presence of 67 possible H\textsc{ii} regions and two optical SNR candidates.

Thuan et al. \cite{62} report the XMM-Newton results of NGC 2366 indicating the existence of two faint X-ray point sources and two faint extended sources. These authors assigned one of these point sources to a possible background active galactic nucleus (AGN), while the other source was found to be coincident with a very luminous star and a compact H\textsc{ii} region. Their two faint extended sources were reported to be possibly associated with massive H\textsc{ii} regions. An-
other study by Stevens and Strickland [59] was the first ROSAT PSPC survey of Wolf-Rayet (WR) galaxies, including NGC 2366. In their study, NGC 2366 was described as a dwarf starburst barred spiral galaxy with an AGN. NGC 2366’s ROSAT PSPC X-ray position was found to be RA(J2000)=07$^h$28$^m$24$^s$, Dec.(J2000)=69°11′0″. These authors traced out WR galaxies and made a possible detection of WR stars in NGC 2363 as was earlier reported by Drissen et al. [12]. Gonzalez-Delgado et al. [18] presented an optical study of NGC 2363 and found broad emission lines at $\lambda$4660 and $\lambda$5810 Å indicating the presence of WR stars. They reported a combined mass of these stars of $3.4 \times 10^5$ $M_\odot$, suggesting the existence of a strong outflow, possibly due to the blow-out of a superbubble. Radio observations with lower resolution suggested the emission from NGC 2366 as a whole should be dominated by thermal emission [66]. Stevens and Strickland [59]’s conclusion was that they detected an extended region, however rather with ambiguity. They provided an optical image superimposed with X-ray contours, pointing to a faint extended X-ray emission coming from the nearby star-forming region in NGC 2363 with a contour level of $2.8 \times 10^{-3}$ count s$^{-1}$ arcmin$^{-2}$. They also found an X-ray point source that might be associated with NGC 2366. The X-ray point source was too faint to obtain a proper spectral fit, but in order to provide its X-ray luminosity they fitted a spectral model with a temperature of $kT = 0.52$ keV, a metallicity of 0.1 $Z_\odot$, and a column density of $4.52 \times 10^{20}$ cm$^{-2}$. With this fit, they obtained an unabsorbed X-ray luminosity of $6.61 \times 10^{37}$ erg s$^{-1}$. However, they argued that it could be an underestimation of the real X-ray luminosity in case the actual galactic column density was higher. Therefore, they did not report best-fit values for their analysis. We will compare our possible SNR candidates locations obtained in this work with their corresponding X-ray positions.

Here, we report a detailed study of optical CCD imaging and spectroscopic analysis of NGC 2366. Since there were no X-ray data available other than those summarised here obtained by several authors as indicated above, we could not perform any X-ray data analysis and therefore could not report them here but rather we made some comparison with possible SNR locations obtained in this
Table 1: NGC 2366 properties.

| Parameters                      | Value                         | References     |
|---------------------------------|-------------------------------|----------------|
| Morphological Type              | IB(s)m                        | Herrmann et al. [21] |
| Position (J2000)                | \( RA(J2000) : 07^h 23^m 51^s .85 \) | Cotton et al. [9] |
|                                 | \( Dec.(J2000): \ Dec.(J2000)=69°12’31”.10 \) |                |
| Redshift                        | 0.000330                      | Paturel et al. [47] |
| Distance                        | 3.44 Mpc                      | Tolstoy et al. [64] |
| Diameter                        | 7.36 kpc                      | *              |
| B-band effective radius consistent with Lyman-break analogs | \( r_{1/2} = 2.7 \pm 0.1 \) kpc | Hunter et al. [22] |

*: [http://annesastronomynews.com/photo-gallery-ii/galaxies-clusters/ngc-2366/](http://annesastronomynews.com/photo-gallery-ii/galaxies-clusters/ngc-2366/)

work and the early limited X-ray results published so far.

Our work is structured as follows. The description of the observations and data reduction is given in Section 2. Our discussion and conclusions can be found in Section 3. The fundamental physical properties of NGC 2366 are given in Table 1.

2. Observations and Data Reduction

The observations are performed in three different epochs by using the Russian-Turkish–Telescope (RTT150). The first epoch is on 29th of March 2017 (CCD1), the second epoch is on 23rd - 24th of December 2017 (CCD2) and the third epoch is on 9th - 10th September 2018 (CCD2). The seeing conditions were consistent throughout the whole observations within a range of 1.8–2.0 ”.

2.1. Imaging observations

The RTT150 has a Ritchey-Chrétien optical system functioning together with Cassegrain and Coude focal systems. We used a TFOSC-CCD, with the

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3Specifications of RTT150 and TÜBİTAK Faint Object Spectrometer and Camera (TFOSC) are available at [http://www.tug.tubitak.gov.tr](http://www.tug.tubitak.gov.tr)
Table 2: Specifications of the CCDs on RTT150 Telescope.

| Properties   | CCD1                     | CCD2                     |
|--------------|--------------------------|--------------------------|
| Pixel Format | 2048 × 2048 pixel        | 2048 × 2048 pixel        |
| Pixel Sizes  | 15 µm                    | 13.5 µm                  |
| Image View   | 13.3 × 13.3 arcmin²      | 11.3 × 11.3 arcmin²      |

Table 3: The filter characteristics and exposure times.

| Filter | Wavelength (Å) | FWHM (Å) | Exposure times (s) | Observations date                  |
|--------|----------------|----------|--------------------|------------------------------------|
| Hα     | 6563           | 80       | 3 × 300            | 29th March 2017                    |
|        |                |          | 6 × 900            | 23rd - 24th December 2017          |
|        |                |          | 6 × 900            | 9th - 10th September 2018          |
| Hα cont.| 6446           | 123      | 1 × 300            | 29th March 2017                    |
|        |                |          | 6 × 300            | 23rd - 24th December 2017          |
|        |                |          | 6 × 300            | 9th - 10th September 2018          |
| [S II] | 6728           | 54       | 3 × 300            | 29th March 2017                    |
|        |                |          | 6 × 900            | 23rd - 24th December 2017          |
|        |                |          | 6 × 900            | 9th - 10th September 2018          |
| [S II] cont. | 6964       | 350      | 1 × 300            | 29th March 2017                    |
|        |                |          | 6 × 300            | 23rd - 24th December 2017          |
|        |                |          | 6 × 300            | 9th - 10th September 2018          |

f/7.7 focal ratio Cassegrain low resolution faint object spectrograph and camera throughout our observations. Our imaging observations were completed by using Hα, Hα cont., [S II] and [S II] cont. narrow band filters. The technical properties of the CCDs (i.e. CCD1 and CCD2) used during our three epochs of observations are given in Table 2. The log of the optical observations are shown in Table 3.
2.2. Imaging data analysis

The raw data was processed by using an Image Reduction and Analysis Facility (IRAF\textsuperscript{4}) for data reduction and also by The European Southern Observatory Munich Image Data Analysis System (ESO-MIDAS\textsuperscript{5}).

Standard procedures were used for data reduction, which include the bias corrections, overscan at field, and cosmic ray elimination by making use of the IRAF CCDPROC package and MIDAS CCDRED application packages. To inspect the locations of the stars, positions of red stars from the USNO A2.0 catalog Monet et.al.\textsuperscript{15} were implemented. Fig.\textsuperscript{1} presents the positions of the SNR candidates overlaid on the Digitized Sky Survey (DSS\textsuperscript{6}) image of the NGC 2366 galaxy. [S\textsubscript{ii}]-[S\textsubscript{ii}] cont. and H\textalpha-H\textalpha cont. images were obtained after achieving the second step from the cleaned images. Finally, the [S\textsubscript{ii}]/H\textalpha ratio can be reached by forming the ratio of these above mentioned two images. Standard stars Feige34, HR 5501 and HR 8634 [see e.g.\textsuperscript{35, 19, 20}] were both observed to calibrate its optical flux.

We began the selection process of candidate SNRs in NGC 2366 by constructing continuum-subtracted H\textalpha and [S\textsubscript{ii}] \(\lambda\lambda 6716, 6731\) images and calculating the [S\textsubscript{ii}]/H\textalpha image ratios. The regions having image ratio values \(\geq 0.4\) were identified as candidate SNRs\textsuperscript{17}.

Preliminary SNR candidates were found by blinking between continuum-subtracted [S\textsubscript{ii}] and H\textalpha sub-field images. For visual inspection of the fields to search for candidates, we produced images of a 2' \(\times\) 2' region. The bright features in the continuum-subtracted [S\textsubscript{ii}] image were checked against the continuum-subtracted H\textalpha image to make sure that the stars were not crudely subtracted. If any feature seen on the [S\textsubscript{ii}] image looked brighter than it was in the H\textalpha image, we tagged it as a candidate SNR, a possible target for follow-up spectral observations.

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\textsuperscript{5}developed by USA National Optical Astronomical Observatories (NOAO)-
https://iraf-community.github.io/

\textsuperscript{6}http://www.eso.org

\textsuperscript{8}https://archive.eso.org/dss/dss
We made use of the [S\textsc{ii}], H\textalpha\ images and their continuum-subtracted images to measure the total counts for each candidate SNR. Then a circular aperture in the continuum-subtracted images was chosen to sum the Analogue to Digital Units (ADU) counts. A concentric annulus region was applied to pick the background counts, which were later subtracted from the aperture sum.

The seeing was obtained during interference filter imaging observations (namely, $1.9''$ corresponding to $\sim 32$ pc for the assumed distance to NGC 2366 of 3.44 Mpc), which is implemented in constraining the aperture sizes used for the measurements of fluxes. We did not include radii calculations for the detected SNR candidates, because of the differences we found between seeing and pixel scales. We used data from Cardelli et al. [5] to correct flux values for interstellar extinction.

Jacoby et al. [24] gave a description of the conversion process from instrumental counts into physical units of (erg cm$^{-2}$ s$^{-1}$). Fig. 1 shows the combined three epochs H\textalpha\ image of NGC 2366 with J(2000) coordinates. Detected possible SNR candidates are shown together with their numbers of 1, 2, 3, 4. Individual images in each filter were aligned and combined with the combine packages of IRAF and ESO-MIDAS. The combination of these data sets are appropriate for the particular analysis presented in the paper. During these observations two different CCDs were used as can be seen from Table 2. CCD1 and CCD2 have almost identical angular resolution, and their quantum efficiencies are similar to each other as well as their seeing between our three epochs of observation.

To be able to get better statistics and therefore better scientific results, we have decided to combine the imaging data for three epochs with the two CCDs. The possible SNR candidates obtained from the combined data are shown in Fig. 1.

A total of four possible SNR candidates near the central part of the NGC 2366 with appropriate [S\textsc{ii}]/H\textalpha\ ratio and three H\textsc{ii} regions are suggested by us, from the combined data as shown in our Table 4 and in Fig. 1 top panel.
Table 4: Combined optical imaging data for the four SNR candidates (SNR1, SNR2, SNR3, SNR4), their corresponding radio coordinates reported by Chomiuk and Wilcots [7] of our IDs of SNR1, SNR2, SNR3, SNR4 and three H II regions (1, 2, 3) with their Hα fluxes, [SII]/Hα ratios and their errors. SNR1, SNR2 and H II 1 correspond here to the two optical SNR candidates and one H II region respectively, as reported by Vučetić et al. [65] and are shown as Vuc5, Vuc34 and Vuc 52.

| ID     | Optical Coordinates | Radio Coordinates | [SII] / Hα | I (Hα) × 10^{-15} |
|--------|---------------------|-------------------|------------|--------------------|
|        | RA(J2000)           | RA(J2000)         |            | (erg cm^{-2} s^{-1}) |
|        | Dec.(J2000)         | Dec.(J2000)       |            |                    |
| SNR1   | 07°28’30”          | 07°28’30”         | 0.68       | 2.10               |
|        | 69°11’33”60        | 69°11’33”80       | (±0.05)    |                    |
|        | (Vuc 5)*            |                   |            |                    |
|        | (Cho 07)*           |                   |            |                    |
| SNR2   | 07°28’52”          | 07°28’52”         | 0.57       | 0.36               |
|        | 69°12’53”00        | 69°12’54”40       | (±0.04)    |                    |
|        | (Vuc 34)*           |                   |            |                    |
|        | (Cho 15)*           |                   |            |                    |
| SNR3   | 07°28’58”          | 07°28’58”         | 0.55       | 0.14               |
|        | 69°13’41”80        | 69°13’41”00       | (±0.02)    |                    |
|        | (Cho 18)*           |                   |            |                    |
| SNR4   | 07°28’45”          | 07°28’45”         | 0.75       | 0.11               |
|        | 69°12’20”70        | 69°12’19”80       | (±0.05)    |                    |
|        | (Cho 12)*           |                   |            |                    |
| H II 1 | 07°29”01”          |                   | 0.11       | 0.05               |
|        | 69°13’30”          |                   | (±0.01)    |                    |
| H II 2 | 07°28”57”          |                   | 0.26       | 0.13               |
|        | 69°13’33”          |                   | (±0.01)    |                    |
| H II 3 | 07°29”04”          |                   | 0.09       | 0.07               |
|        | 69°13’31”05        |                   | (±0.01)    |                    |

Notes. * From Vučetić et al. [65], † From Chomiuk and Wilcots [7].
2.3. Spectral observations

Our spectral observations were performed by using the Cassegrain-TFOSC / CCD of RTT150. Spectral measurements were obtained in the $\lambda 3230$–9120 Å range with the grism G15. In total spectra of 5 different regions have been analysed. For the flux calibration, we have observed the standard stars (Feige34, HR 5501 and HR 8634) as our spectrophotometric standards as suggested by [see e.g. 35, 19, 20]. Fe-Ar calibration lamp frames were obtained for slit width for each observation. High-resolution long-slit spectra of two possible SNR candidates, SNR1 and SNR4, are reported here together with those of three possible detected H ii regions (H ii-1, H ii-2 and H ii-3).

2.4. Spectral data analysis

The spectroscopic observations were performed on March 29, 2017 (Epoch 1) and September 9, 2018 (Epoch 3) with the RTT150 using the medium resolution spectrometer TFOSC. The grism G15 with the nominal dispersion of $\sim 8$ Å pixel$^{-1}$ was used. The reduction and analysis of a spectrum are made using the package Longslit context of IRAF. The exposure time for each spectrum is 3600 s. The slit width we used during our spectral observations was 1.78′′ (100 µ). The resolution at H$\alpha$ is 16 Å.

The ratio [S ii]/H$\alpha$ and the electron density are calculated from the [S ii] ($\lambda 6716/\lambda 6731$) flux ratios following the work done by Osterbrock and Ferland [41]. Using the [O iii]$\lambda 5007$/H$\beta$ line ratio, the shock velocities, $V_s$, proposed for extragalactic SNRs are estimated from the study of Matonick and Fesen [37] and the measurements of [O iii]$\lambda 5007$/H$\beta$ ratios reported by Dopita et al. [11] providing an estimate for the [O iii]$\lambda 5007$/H$\beta$ ratio as a function of shock velocity. These authors also provided the plots of this ratio in their Figs 5 and 6 in terms of $V_s$. Our [O iii]$\lambda 5007$/H$\beta$ ratio range (2.61–3.57) is obtained from our individual spectral analyses for the four SNR candidates and the shock velocities of H$\alpha$ were produced by a dust screen distribution using the relations of Relano et al. [49], Buat et al. [4] as can be seen from Table 5.
The interstellar extinction and the extinction of Hα produced by such a dust screen distribution were also determined through the relations of Relano et al. [49], Buat et al. [4] together with Neutral Hydrogen column density relation from Predelh and Schmitt [48]. This is similar to the determinations reported for another nearby galaxy by Erkan et al. [14].

The spectral parameters of SNR1 and SNR4, including the relative line flux and electron density ($N_e$) parameter were derived from the [SII]($\lambda 6716/\lambda 6731$) ratios for an assumed electron temperature of $10^4$ K [41].

The spectra of our possible candidates SNR1 and SNR4 together with those of the three possible HII regions of 1, 2, and 3 in the range of $\lambda 4500$−$7000$ Å, are presented in Table 5 and Fig. 2 and Fig. 3. Our results for SNR1 and SNR2 are found to be consistent with the optical observations reported recently by Vučetić et al. [65]. However, our SNR3, SNR4, HII-2 and HII-3 have not been detected by these authors. The limiting flux sensitivity of our imaging observations is obtained by taking a blank and faintest part in a circle same circular aperture with our 4 SNRs and found to be $0.037 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$.

In Drissen et al. [13] NGC 2366BG7, located at $RA(J2000) = 07^h28^m45^s.3$, $Dec.(J2000) = 69^\circ12'19''2$ is reported as one of the background galaxies in the direction of NGC 2366 by using MKR 71 and NGC 2363 Hubble Space Telescope (HST) data. Its position is found to be consistent with our SNR4. It is also consistent with one of the five radio SNRs suggested by Chomiuk and Wilcots [7] as their one out of five SNRs so-called Cho 12.

Chomiuk and Wilcots [7] reported radio observations of NGC 2366 and suggested the sources Cho 07, Cho 15, Cho 18 and Cho 12 to be possible SNR candidates. In this study, our possible four SNR candidates (see Table 4) are all found to be in a good agreement with their 20 cm radio locations. Our HII regions reported here are consistent with the findings of Vučetić et al. [65] results.

$^7$calculated with The Space Telescope Science Data Analysis System (STSDAS) task nebular.temden program; this task is based on the program FIVEL [50, 54] for a five level atom
Table 5: Relative line intensity for the SNR candidates (SNR1 and SNR4). Fluxes are normalised \( F(\text{H} \alpha) = 100 \). The signal-to-noise ratios (S/N) of the emission lines are given together with other physical parameters.

| Lines (Å)          | SNR1     | SNR4     |
|-------------------|----------|----------|
|                   | F        | S/N      | F        | S/N      |
| \( \text{H} \beta (\lambda 4861) \) | 31.36    | 5        | 18.70    | 4        |
| \[\text{O} \text{iii} \] (\( \lambda 4959 \)) | 36.92    | 5        | 37.40    | 9        |
| \[\text{O} \text{iii} \] (\( \lambda 5007 \)) | 111.80   | 15       | 48.78    | 5        |
| \[\text{N} \text{ii} \] (\( \lambda 6548 \)) | 28.25    | 12       | 24.39    | 5        |
| \( \text{H} \alpha (\lambda 6563) \) | 100      | 15       | 100      | 18       |
| \[\text{N} \text{ii} \] (\( \lambda 6584 \)) | 43.16    | 6        | 32.52    | 6        |
| \[\text{S} \text{ii} \] (\( \lambda 6716 \)) | 36.97    | 5        | 42.28    | 4        |
| \[\text{S} \text{ii} \] (\( \lambda 6731 \)) | 36.56    | 5        | 40.65    | 4        |

| Parameters & Line Ratios | SNR1     | SNR4     |
|--------------------------|----------|----------|
| I (\( \text{H} \alpha \)) (10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}) | 1.92 ± 0.04 | 0.12 ± 0.03 |
| \[\text{S} \text{ii} \] \text{a} / \( \text{H} \alpha \) | 0.74 ± 0.11 | 0.82 ± 0.08 |
| \[\text{S} \text{ii} \] \( \lambda 6716/\lambda 6731 \) | 1.01 ± 0.08 | 1.04 ± 0.07 |
| \[\text{O} \text{iii} \] (\( \lambda 5007 \))/\( \text{H} \beta (\lambda 4861) \) | 3.57 ± 0.07 | 2.61 ± 0.14 |
| \( V_c \) (km s\(^{-1}\)) | 80–100   | 80–100   |
| \( E(B - V) \) | 0.36 ± 0.06 | 0.26 ± 0.07 |
| \( A_{(\text{H} \alpha)} \) | 0.25 ± 0.06 | 1.43 ± 0.07 |
| \( N(\text{H} \text{I}) \) (10^{20} \text{ cm}^{-2}) | 2.42 ± 0.05 | 13.80 ± 0.2 |
| \( N_c \) (cm\(^{-3}\)) | 581.91 ± 168.61 | 513.38 ± 135.88 |

Notes. \text{a} \[\text{S} \text{ii} \] is the combination of the \( \lambda 6716 \) and \( \lambda 6731 \) flux values.
In order to verify the photometric calibration, Hα fluxes of our possible SNR candidates are compared and given in our Table 5. Our flux values are found to be in the range of \((0.11 - 2.10) \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\). Vučetić et al. [65]'s work of optical imaging observations revealed the existence of two optical SNR candidates together with their characteristics of Hα and [S\,\text{II}] fluxes across the two fields of view in NGC 2366. Our SNR1 and SNR2 locations are consistent with their findings. However, our SNR3 and SNR4 are consistent with the radio results given by Chomiuk and Wilcots [7] which may indicate the possible existence of two new optical SNR candidates in NGC 2366.

Vučetić et al. [65] reported 67 possible H\,\text{II} regions in their work and their so-called Vuc 52 is consistent with our H\,\text{II}-1 position as shown in our Table 4. The XMM-Newton X-ray position given at \(RA(J2000) = 07^h28^m58^s.2, Dec.(J2000) = 69^\circ11^\prime34^\prime\) by Thuan et al. [62] is found to be very close when compared with 5th radio position reported by Chomiuk and Wilcots [7].

3. Discussions and conclusions

In this work, we present an optical study for the SNR candidates using narrow-band images and their spectra obtained with RTT150-TUG for the first time. We have identified four possible SNRs, with appropriate [S\,\text{II}]/Hα ratios and three possible H\,\text{II} regions. Our conclusions are;

(i) From optical imaging, the ratio \([\text{S\,II}]/\text{Hα} \geq 0.4\) is used in our work to identify the possible SNR candidates. We identified a total of four SNR candidates in NGC 2366 together with a possible existence of three H\,\text{II} regions using our combined optical data. Out of four SNR candidates reported here, the two of them are newly discovered SNR candidates in NGC 2366. New spectroscopic observations of five of these sources (SNRs & H\,\text{II} regions) are presented as well.

(ii) Spectral analyses are also performed here for two of our possible SNR candidates in NGC 2366. We report the range of line fluxes and the
parameters of $[\text{S} \text{II}]/\text{H} \alpha = 0.74 - 0.82$, $[\text{S} \text{II}]$(λ6716/λ6731) = 1.01 - 1.04, shock wave velocities of $80 < V_s < 100$ km s$^{-1}$, its optical extinction range of $E(B-V) = 0.26 - 0.36$, $A_{(\text{H}\alpha)}$ in the range of 0.25 - 1.43, absorbing column density range of $N(\text{H} \text{I}) = (2.42 - 13.80) \times 10^{20}$ cm$^{-2}$ and electron density range of $N_e = (513 - 581)$ cm$^{-3}$, as shown in Table 5. Two out of four SNR candidate locations reported in this work are found to be consistent with Vučetić et al.'s results. We must point out here that optical flux values we have reported here are found to be consistent with other nearby galaxy SNRs (see e.g. Sonbas et al., Pakmor et al., Taubenberger et al., Leonidaki et al. are mentioned the spectral features of SNRs in nearby galaxies and the relation with their emission lines. A viable model for normally bright SNe Ia, where nebular O I emission had never been observed could be a similar case that fit with our spectral results presented in this study.

(iii) According to Chomiuk and Wilcots radio observations, five radio SNR candidates are reported. All of our possible SNR candidates locations presented here are found to be consistent with four of their SNR positions (see our Table 1).

(iv) The fainter and possibly extended XMM-Newton source J072830.4+691132 reported by Thuan et al. coincides with our SNR candidate SNR1 to within about 2 '', which may suggest its association with a possible SNR candidate when it is considered in junction with our spectral results of SNR1.

Stevens and Strickland’s ROSAT PSPC study of NGC 2366 supported the existence of characteristic extended region at $RA(J\text{2000}) = 07^h28^m24^s$, $Dec.(J\text{2000}) = 69^\circ11'0''$ which is not exactly coincident with any of our observed possible SNR candidates, studied here. However, it can be considered nearest to our SNR1 candidate at $RA(J\text{2000}) = 07^h28^m30^s.7$, $Dec.(J\text{2000}) = 69^\circ11'33''60$. 

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(v) We must emphasize here that in the X-ray band, NGC 2366 has very limited observations and previous X-ray studies outlined above could not contribute much to the existence of possible SNR candidates in this nearby galaxy. Further deep observations are needed by satellites such as Chandra and/or XRISM to achieve a better understanding of the X-ray properties of NGC 2366. For this purpose we are in a stage of submitting a Chandra proposal for a better understanding of the possible SNR candidates and the physics behind them.

(vi) About the SN rate, Chakrabarti et al. [6] reported the SN rates are obtained using the data from Lick Observatory Supernova Search (LOSS). The rate beyond the optical radius of spiral galaxies host $2.5 \pm 0.5$ SNe per millennium. The rates of core-collapse SNe that may collapse to form the massive black holes detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the outer discs of spiral is reported to be $1.5 \pm 0.15$ per millennium and for dwarf galaxies is $2.6 \pm 1.5$ SNe per millennium or in otherwords, $31,000 \pm 18,000$ SNe Gpc$^{-3}$ yr$^{-1}$. The relative ratio of core-collapse to SNe Ia is comparable in the inner and outer parts in dwarf galaxies. There is no SN rate reported. Since there is no reported SN rate for NGC 2366, one can assume that the predicted SNe rate for dwarf galaxies mentioned above may well be applicable for NGC 2366.

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Figure 1: Top Panel: Combined RTT150 data: The Hα image of NGC 2366 with J2000. Possible SNR candidates are given with thick white circles with our SNR1, SNR2, SNR3 and SNR4, which are matched with the radio SNR candidates of Chomiuk and Wilcots [7] are shown. Our H II regions are given with thin white circles H II-1, H II-2 and H II-3 are shown. Bottom Panel: Chomiuk and Wilcots [7] 20 cm radio map of NGC 2366, with J2000, where “+” indicates background galaxies, “circles” their SNR candidates and “⋆” signs are their H II regions.
Figure 2: Spectra of SNR1 and SNR4 (Epoch 1) in λ4500—7000 Å range. Its Balmer Hα λ6563 Å, Hβ λ4861 Å, forbidden lines [O III] λλ4959,5007 Å, [N II] λλ6548,6584 Å, [S II] λλ6717,6731 Å are shown.
Figure 3: Spectra of HII region 1 (Epoch 1), 2 (Epoch 1) and 3 (Epoch 3) candidates in $\lambda 4500 - 7000$ Å range.