

Newly confirmed and candidate Galactic SNRs uncovered from the AAO/UKST H α survey

M. Stupar,^{1,2*} Q. A. Parker^{1,2} and M. D. Filipović³

¹*Department of Physics, Macquarie University, Sydney 2109, Australia*

²*Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia*

³*University of Western Sydney, Locked Bag 1797, Penrith South DC, NSW 1797, Australia*

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ABSTRACT

We present a catalogue of 18 new Galactic supernova remnants (SNRs) uncovered in the optical regime as filamentary emissions and extended nebulosities on images of the Anglo-Australian Observatory/United Kingdom Schmidt Telescope (AAO/UKST) H α survey of the southern Galactic plane. Our follow-up spectral observations confirmed classical optical SNR emission lines for these 18 structures via detection of very strong [S II] at 6717 and 6731 Å relative to H α ([S II]/H α > 0.5). Morphologically, 10 of these remnants have coherent, extended arc or shell structures, while the remaining objects are more irregular in form but clearly filamentary in nature, typical of optically detected SNRs.

In 11 cases there was a clear if not complete match between the optical and radio structures with H α filamentary structures registered inside and along the presumed radio borders. Additionally, *ROSAT* X-ray sources were detected inside the optical/radio borders of 11 of these new remnants and three may have an associated pulsar.

The multiwavelength imaging data and spectroscopy together present strong evidence to confirm identification of 18 new, mostly senile Galactic SNRs. This includes G288.7–6.3, G315.1+2.7 and G332.5–5.6, identified only as possible remnants from preliminary radio observations. We also confirm existence of radio-quiet but optically active SNRs.

Key words: catalogues – surveys – supernova remnants.

1 INTRODUCTION

An up-to-date inventory of Galactic supernova remnants (SNRs) provides key data for improving our understanding of Galactic star formation history and the Galactic energy balance. Unfortunately, the total number of known SNRs (265; Green 2006) compared to those expected (>1000; Case & Bhattacharya 1998) implies there remains a significant population of undiscovered remnants. This is primarily due to various selection effects, such as highly variable extinction and the wide range of observed properties depending on the SNRs evolutionary state. These hamper detection of both the youngest and oldest SNRs of large angular size which are usually highly fragmented. In the modern era, identification and observation of most Galactic SNRs has been predicated by radio detections where their non-thermal spectra and typically coherent radio shell structures and low linear polarization are easy to recognize. Radio observations substantially mitigates the problems of dust which make optical detection so difficult. Indeed, due to the high concentration of dust around the Galactic plane, prior to this paper

only a small fraction of known Galactic SNRs, as detected over a wide range of radio frequencies, have matching optical detections. Green's online SNR catalogue (Green 2006) of 265 Galactic SNRs, the most complete compilation currently available, report optical detection in only ~17 per cent of SNRs. However, radio surveys are not very sensitive to extremely evolved SNRs.

The second major tool in SNR investigations today are X-ray observations via satellites which enables estimation of key parameters such as remnant age, explosion energy and the ambient interstellar density (e.g. Mavromatakis, Aschenbach & Boumis 2004). Here it has been shown that SNR X-ray morphology does not follow the typical radio shell structure. SNRs exhibit more mixed X-ray morphology, typically with filled centres and with both thermal and non-thermal emission (Seward 1990).

Historically, many Galactic SNRs were first detected in the optical via the early wide-field photographic surveys (e.g. Rodgers, Campbell & Whiteoak 1960), particularly in the line of H α . The optical morphology, often filamentary in nature, was seen to follow the outline of the radio shell revealed in subsequent radio observations. Also common was the presence of highly fragmented, narrow, optical filaments or emission clouds of irregular form both inside, outside or on the given radio boundaries.

*E-mail: mstupar@physics.mq.edu.au

Over the last few years a series of papers by an active Greek group (e.g. Boumis et al. 2005, 2007) have been uncovering new, optical SNR detections by targeting many known northern remnants via selected, deep, narrow-band imaging and spectroscopy, reinforcing the value of optical coverage. However, individual narrow optical filaments, elongated arc structures or irregular nebulous clouds cannot be accepted as part of an SNR until other supporting evidence is available, such as provided by non-thermal radio signatures or optical spectra which verify remnant shocked gaseous emission.

Optical spectroscopic signatures typical of SNRs and of shocked gas include strong forbidden line emission such as [S II] 6717/6731 Å, [N II] 6548/6584 Å, [O I] 6300/6364 Å, [O III] 4959/5007 Å and [O II] 3727 Å. The [S II] lines should be strong and particularly high ratios of [S II]/H α which enable a clear distinction between H II regions, most planetary nebulae (PNe) and SNRs where the detected spectral lines are similar. A value of [S II]/H α > 0.5 is often used as the basis for separating SNRs from H II regions and PNe. In fact, Mathewson & Clarke (1973) adopted ~ 0.7 , while Daltabuit, D'Odorico & Sabbadin (1976) suggested ~ 0.5 . Fesen, Blair & Kirshner (1985) accepted [S II]/H α > 0.5 coupled with the presence of strong [O I] and [O II] lines (but only where the spectral resolution permits proper [O I] sky subtraction). The value ([S II]/H α > 0.5) has been used as a key spectral discriminator in this paper, together with the supporting presence of Balmer, [N II], [O II] or [O III] lines.

The Anglo-Australian Observatory/United Kingdom Schmidt Telescope (AAO/UKST) (AAO/UKST) SuperCOSMOS H α survey (SHS hereafter; Parker et al. 2005) with its combination of arcsecond resolution, 5 Rayleigh sensitivity and 4000-deg² coverage, now offers a powerful, new opportunity to revisit the regime of optical SNR detection and discovery across the entire southern Galactic plane. The SHS comprises 233 overlapping fields on 4° field centres (Parker & Philipps 1998). Every survey pointing was exposed for 3 h, accompanied by a matching 15 min broad-band (5900–6900 Å) short red (SR) exposure. The SHS has already resulted in significant discoveries of planetary nebulae (e.g. Parker et al. 2006; Miszalski et al. 2008), Wolf–Rayet stars (e.g. Morgan, Parker & Russeil 2001; Parker & Morgan 2003), H II regions and filamentary nebulosities (Walker, Zealey & Parker 2001) and is a rich source of emission sources of every kind. Detailed confirmations of three SNR candidates based on our SHS discoveries have already been reported by (e.g. Stupar, Parker & Filipović 2007a,b; Stupar et al. 2007c).

For all currently known Galactic SNRs there are only 15 with $|b| > 5^\circ$ and their distribution is quite asymmetric. Only four are in the Southern hemisphere, while the rest are above $\pm 5^\circ$ (Green 2006). Although this asymmetry may be related to Gould's Belt (Stothers & Frogel 1974), there is no evidence of the same asymmetry for low Galactic latitude SNRs, which are not statistically different (Green 2006). The SHS extends to $|b| \sim 10^\circ$ – 12° and provides a fresh opportunity to search for evolved remnants to higher southern latitudes in the optical.

Here we report results of a systematic SHS search, undertaken to improve the detection of both known and new Galactic SNRs across the southern Galactic plane from a non-radio perspective. We present results of our extensive follow-up spectral observations of new candidates obtained during five runs on the 1.9-m telescope of the South African Astronomical Observatory and 2.3-m telescope of Mount Stromlo and Siding Spring Observatory between 2004 and 2006. These observations provided confirmation of the 18 new Galactic SNRs in this paper. We provide compelling evidence for the veracity of these new SNRs through the combination of diagnostic optical spectroscopic signatures and likely radio,

X-ray and pulsar connections with many of the H α morphological structures identified from the SHS. We conclude that most of these new remnants are senile and probably in the dissipation or merging phase with the interstellar medium (ISM). This has made previous identification from the extant radio surveys problematic, due to high levels of fragmentation, but more obvious once the radio survey data are superimposed on the SHS images. We have now added ~ 7 per cent to the total number of remnants recognized in the Galaxy. Many additional candidates still require spectroscopic follow-up and further confirmations will be presented in subsequent papers.

2 IDENTIFICATION OF NEW GALACTIC SNRs IN THE AAO/UKST H α SURVEY (SHS)

Our large-scale, systematic search for new Galactic SNRs was based initially on detection of new, coherent, optical emission structures identified in the SHS (e.g. Stupar et al. 2007a,b,c).

Although the SHS survey is an H α survey, the interference filter used has a central wavelength at 6950 ± 25 Å and full width at half-maximum (FWHM) of 70 ± 3 Å (Parker & Bland-Hawthorn 1998) so both [N II] emission lines at 6548 and 6584 Å are included. These contributions can only be effectively deconvolved via spectroscopy. However, this exceptional monolithic H α filter avoids problems with previous segmented filters (Meaburn 1980) and provides a very uniform survey once flat-fielded (Parker et al. 2005). Using the SuperCOSMOS measuring machine at the Royal Observatory Edinburgh (Miller et al. 1992), the matching H α and SR images were transformed into digital form and have been available online since 2003.¹ For practical access reasons, only 900 arcmin² of pixel data as FITS images can be downloaded at a time. The pixel data for each survey field is about 2 GB. Every downloaded fits image has accurate in-built astrometry (world coordinate system).

2.1 Examination of SHS blocked-down data

Downloading 30×30 -arcmin² full resolution images of the entire 4000 deg² of the H α survey was impractical so, an initial search for large, coherent H α emission structures was undertaken using the 16×16 blocked FITS images of all survey fields which are also online. An advantage of the blocked-down data is that large-scale, low surface brightness features are enhanced. However, the resolution is relatively low (~ 11 arcsec) but still compares favourably with the 48-arcsec resolution of the SHASSA online H α survey (Gaustad et al. 2001). All 233 blocked-down SHS fields were carefully examined to identify about 60 new candidate emission structures. The right ascension (RA)/declination (Dec.) coordinates of these candidate regions were then used to extract full resolution SHS images of appropriate size for detailed study. This strategy enabled all 233 survey fields to be examined efficiently and provided many decent candidates but there is a problem. Smaller scale, fractured and fine filamentary and weak emission features can easily be overlooked in the blocked-down images yet these are some of the best optical manifestations of evolved remnants.

2.2 Examination of original H α survey films

Due to resolution limitations of the blocked SHS data coupled with the download field size restrictions of the high-resolution images,

¹ <http://www-wfau.roe.ac.uk/ss/halpha/>.

examination of the original survey fields was undertaken at the Plate Library of the Royal Observatory Edinburgh (ROE) in August 2004 where the original H α and counterpart SR films are archived. 29 further small-scale filaments and diffuse emission candidates (see example in Stupar et al. 2007a) were found in addition to the ~ 60 candidates uncovered from the blocked-down FITS images. The visual search of the original films did not cover the regions around the Galactic Centre or Vela SNR as both areas are exceptionally rich in emission filaments which requires much more detailed examination.

During scrutiny of the SHS it was noticed that some of the brighter components of candidate SNRs detectable with existing broad-band optical surveys are already in the literature as nebulosities of unknown nature or as H II regions. Many of these putative H II regions, identified by their morphological structure on broad-band images have no spectra to verify their true nature. The SHS sensitivity and resolution reveals far more extensive and distinct features of these regions which brings in to question their original H II identification.

For the first time, we have also uncovered optical filaments and diffuse emissions associated with ~ 30 known Galactic SNRs previously detected solely via their radio signatures (e.g. Stupar et al. 2007b).

2.3 Checks against catalogues of existing nebulous objects

Previously identified Galactic H II regions and evolved planetary nebulae can appear similar to SNRs in their optical morphological structure so new remnant candidates were first checked against the SIMBAD² data base of catalogued nebulae and against the extensive list of ~ 1250 new ‘MASH’ PNe also discovered from the SHS (Parker et al. 2006; Miszalski et al. 2008). A further check was done against Wolf–Rayet stars with known nebulosities. These stellar outflows sweep up the surrounding material creating a nebulae or interstellar bubble which can appear similar to an SNR shell. In the optical regime, like SNRs, these structures can be recognized in H α and [O III] light (Chu, Treffers & Kwitter 1983). A further check against entries in the 7th Catalogue of Galactic Wolf–Rayet stars (van der Hucht 2001) was also done to eliminate candidates that are actually just newly identified nebulosities associated with previously bare WR stars, now made possible with the SHS.

2.4 Comparison with extant radio data

The most important comparison is with possible radio detections, whether previously associated with a candidate remnant or not. Data for four radio surveys were examined: the PMN at 4850 MHz (Condon, Griffith & Wright 1993), the SUMSS at 843 MHz (Cram, Green & Bock 1998), the Parkes 2400 MHz survey of the southern Galactic plane (Duncan et al. 1995) and the northern NVSS 1.4-GHz (up to $\delta = -40^\circ$) continuum survey (Condon et al. 1998). These data were used to establish any possible connection between radio structures and our newly discovered optical SNR candidates.

Possible radio–optical matches were checked via contouring of the best radio flux images and overlaying these on a grey-scale of the H α images. In some cases an excellent match was found between the new optical filamentary structures and the radio contour data, (see Stupar et al. 2007a). These present excellent candidates for further confirmatory, multifrequency follow-up.

3 OPTICAL SPECTROSCOPIC OBSERVATIONS

The five spectroscopic runs awarded were insufficient to observe all of our SNR candidates due to poor weather. Remaining candidates will form the basis of a subsequent publication once follow-up is available. Two runs were at the 1.9-m SAAO telescope (in 2004 July and 2006 February) and three runs at the 2.3-m MSSSO (in 2004 June and 2005 June and August). After the spectra were obtained and reduced, the ratios of key emission lines were used in diagnostic plots to aid classification as new SNRs or other object types accordingly.

For primary object classification, low-resolution SAAO 1.9-m spectra (~ 7 Å between 3500 and 7500 Å) were used, and medium resolution MSSSO 2.3-m blue (~ 2.2 Å between 3500 and 5400 Å) and red (~ 1.1 Å between 6100 and 6900 Å) spectra were used. If the low-resolution spectra showed promising SNR lines and ratios, the same object was re-observed with a higher dispersion red grating to cover the H α and [S II] lines for improved radial velocities.

From the observing runs, 18 SNR candidates were confirmed following the line ratio diagnostic criteria of Fesen et al. (1985) and results are presented here. For ~ 30 candidates their spectra did not confirm shocked material and the majority of these nebulae are previously uncatalogued H II regions which will be reported in a separate publication.

All spectroscopic runs suffered non-photometric nights so proper extinction estimates could not be calculated directly from the spectra. Hence, for the relative strength of spectral lines (and their ratio), $F(\lambda)$ instead of extinction corrected $I(\lambda)$ was used.

For data reduction standard IRAF slit-spectra routines were used. For flux calibration standard spectrophotometric stars were observed each night when possible from the lists of Hamuy et al. (1992, 1994). The Starlink FIGARO package BCLEAN was used for cosmic ray rejection while extraction of 1D spectra was facilitated via supplementary IRAF and perl scripts developed by Brent Miszalski.³

Table 1 presents the main characteristics for all 18 SNR candidates. The first column gives the standard remnant ID as truncated Galactic coordinates. For Galactic SNRs the attributed name is usually formed from the Galactic coordinates of the remnant’s centre (usually in the form of a shell) where the progenitor star was probably located before the supernova explosion. Due to the irregular structure of these newly uncovered filaments/clouds it was often not possible to properly define the overall shape of the SNR from the optical data nor to estimate the centre of the observed structures. Under these circumstances, the SNR name was taken from the Galactic coordinates of the slit position used to obtain the primary optical spectrum, usually taken across the most prominent optical structure. Exceptions are G288.7–6.3, G292.9+4.5 (RCW 59), G315.1+2.7 and G332.5–5.6 previously known as SNR candidates or H II regions (RCW 59). In Table 1 we also include the ratio of the [S II]/H α lines as this is the most important spectroscopic diagnostic to separate SNRs from H II regions and most planetary nebulae. If the optical imagery and spectral confirmation is supported with any radio, X-ray or pulsar detection in the vicinity this is also noted.

For determining the uncertainties in the flux estimates the IRAF task splot was used to fit Gaussian profiles to provide both fluxes and a standard deviation σ which was also used as an average measure of the Gaussian line profile of all brightest lines. The flux error for the

² <http://simbad.u-strasbg.fr/>.

³ <http://www.aao.gov.au/local/www/brent/pndr/>.

Table 1. The main characteristics of the newly discovered SNR candidates.

Standard ID	RA J2000.0	δ J2000.0	Extent (arcmin)	[N II]/H α (average)	[S II]/H α (average)	Average [S II] 6717/6731	Radio	X-ray	Pulsar	Remarks
G253.0+2.6	08 25 54	−33 26 09	6	1.07	1.16	1.11	Y?	N	N	
G243.9+9.8	08 28 58	−21 57 43	16	0.65	0.89	1.55	Y	N	N	Brandt 152
G283.7−3.8	10 05 23	−60 17 07	120	1.38	1.47	1.33	N	Y	N	
G288.7−6.3	10 26 40	−64 41 13	2.5	0.46	0.54	0.93	Y	Y?	N	Radio SNR candidate
G281.9+8.7	10 41 04	−48 48 49	150	1.39	3.59	1.40	N	Y	N	
G288.3+4.8	11 07 19	−55 05 00	5, 15	0.62	1.46	1.37	N	Y	N	
G289.7+5.1	11 17 02	−55 17 11	7, 15, 22	0.60	1.38	1.40	Y	Y	N	
G289.2+7.1	11 18 35	−53 18 01	30	0.71	1.80	1.29	N	Y?	N	
G292.9+4.4	11 41 42	−57 20 00	100	0.65	0.97	1.40	Y	Y?	N	RCW 59
G303.6+5.3	12 56 31	−57 30 21	240	0.58	0.74	1.42	N	Y	Y	
G306.7+0.5	13 23 35	−62 05 41	25	0.55	0.85	1.36	Y?	Y	Y	
G315.1+2.7 ^a	14 33 25	−57 35 30	11	1.42	1.13	1.41	Y	Y?	N	
G332.4+0.6	16 13 01	−50 21 59	30	1.12	1.02	1.20	N	N	Y?	
G343.4+3.6	16 43 03	−40 37 44	4, 7	0.81	0.59	1.35	Y	N	N	
G332.5−5.6 ^a	16 42 17	−54 28 33	30	2.42	1.92	1.23	Y	Y	N	
G329.9−7.8	16 43 14	−58 00 15	7	1.77	1.18	1.27	N	N	N	
G348.2−1.8	17 21 49	−39 51 26	5, 8	0.94	0.82	1.42	Y	N	N	
G18.7−2.2	18 33 07	−13 38 52	30(120?)	0.72	1.33	1.34	Y?	N?	N?	

^aIndicates the two new confirmed remnants which have already been published separately.

brightest lines with the SAAO 300 lines mm^{−1} grating was between 5 and 10 per cent, while for the medium-resolution 1200 lines mm^{−1} red grating it was around 20 per cent. This is not unexpected due to the generally lower signal-to-noise ratio (S/N) obtained for the higher resolution spectra. For the MSSSO 2.3-m blue grating (600 lines mm^{−1}) this error is between 10 and 20 per cent and for the red grating (1200 lines mm^{−1}) it is between 15 and 25 per cent. Due to the lower detector sensitivities in the blue the spectral region between 3500 and 4000 Å has low S/N. Unfortunately, the valuable diagnostic [O II] 3727-Å emission doublet is located here and flux calibration of this particular line was often very uncertain.

3.1 Other detected SNR diagnostic emission lines

The most prominent optical spectral diagnostic for SNRs is the ratio of [S II]/H α being >0.5 which indicates the presence of shocks. Shocks arise from other astrophysical phenomena but high values of this ratio are strongly indicative of an SNR. Only two of the new SNRs have this value <0.7 while for 12 new remnants this value is ≥ 1 for at least one slit position. There are other line ratios that are important in supporting SNR classification such as the ratio of the [O III] lines (4959 + 5007)/4363 (an electron gas temperature indicator) having a value <30 (Fesen et al. 1985) which implies electron gas temperatures in excess of 20 000 K, values never seen even in the hottest H II regions. Our observations are of faint new remnants with modest spectral S/N so these very faint lines are not detected and play no part in our classification.

The oxygen [O I] lines at 6300 and 6364 Å are present and often prominent in most SNR candidate spectra. This is not the case for H II regions or usually PNe. Unfortunately, these lines are also strong in the night-sky spectrum and are susceptible to imperfect sky-subtraction as the nebulae usually extend quite a way across the slit. Even with careful sky subtraction the expected 6300/6364 Å lock-step ratio of 3:1 was often not achieved due to the modest spectral resolution so the flux values for these lines are not reliable. However, [O I] detection is often verified from careful examination of the 2D spectral image. Other typical SNR emission lines are

sometimes seen in our sample, such as [Ne III] + H at 3970 Å or He + H at 3888 Å (Fesen et al. 1985). The Balmer lines (in different strengths) are always present in the observed SNR candidate spectra but are not recorded for brevity and detection in the blue depends on extinction.

3.2 The new SNR catalogue

We present details and H α images of all 18 new SNR candidates that have passed the various selection criteria. For objects where a clear radio connection at 843 MHz (SUMSS radio survey), 1400 MHz (VLA NVSS radio survey), 2400 MHz (Parkes radio survey) or 4850 MHz (PMN radio survey) has been found, the radio contours were overlaid on the optical image as support of the SNR classification. In a few cases radio detections at several frequencies was noticed, offering the potential to measure a spectral index to further bolster the SNR classification (e.g. G332.5−5.6), but in most instances only single frequency detections are possible from the existing radio surveys. Targeted multifrequency follow-up of these new SNRs is required to reveal their non-thermal nature.

Any association of a candidate with an X-ray source or possible pulsar in close proximity is also indicated in the catalogue even though it is often hard to establish a definite connection between these objects and our candidates. Some images also indicate the slit position(s) for the spectroscopic follow-up. Candidates are presented according to increasing RA as in Table 1.

G253.0+2.6. This candidate was first recognized as a discrete group of H α filaments (Fig. 1) where the largest arcuate filament is about 6 arcmin at maximum extent and was discovered on SHS field HA528. Due to the large overlap that exists between adjacent SHS survey fields, this structure was also clearly visible on survey field HA602, confirming its veracity. Two SAAO 1.9-m low-resolution spectra were obtained along the major filament sampled about 2.5 arcmin apart exhibiting typical SNR characteristics with strong [N II] and [S II] lines.

The PMN 4850-MHz radio survey data in the region show some weak detection though precise details are not possible due to the low survey resolution (FWHM of the 43-m dish is ~ 7 arcmin).

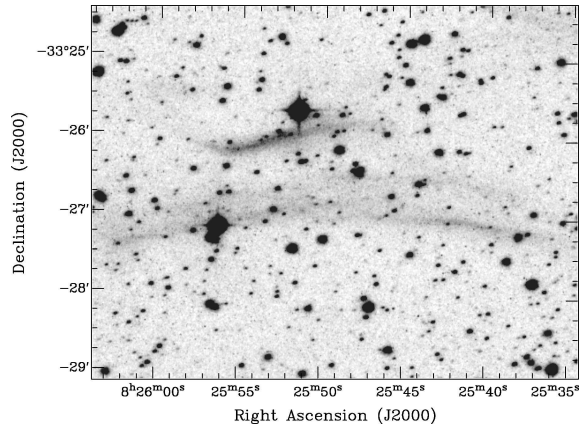


Figure 1. G253.0+2.6. The group of filaments concentrated around RA = $08^{\text{h}}25^{\text{m}}50^{\text{s}}$, $\delta = -33^{\circ}25'30''$. The extent of the largest arcuate filament is ~ 6 arcmin. Fragmented filaments occupy an area of ~ 8 arcmin.

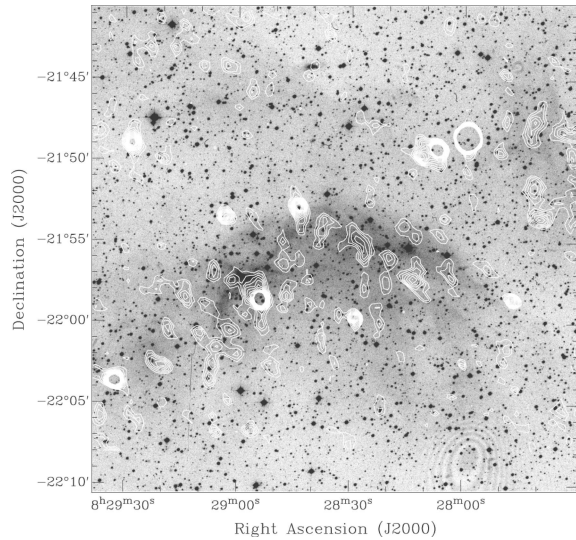


Figure 2. 30×30 arcmin² field around G243.9+9.8. The H α image is overlaid with the NVSS 1.4-GHz continuum survey contours. The strongest contours are 0.006 Jy beam⁻¹. Although highly fragmented there is a clear excess of radio power following the main optical arc structure. The faint elliptical forms in the lower right-hand corner are interference patterns (Newton's rings) due to the SuperCOSMOS glass platten used to sandwich the SHS Tech-Pan films in place during scanning.

No detection was found in the VLA NVSS 1.4-GHz survey (which covers up to -40° in declination), while the SUMSS 843 MHz does not cover this area of sky. Further radio observations are warranted.

G243.9+9.8. This is a large, prominent, arcuate nebula (Fig. 2) about 16 arcmin at maximum extent discovered on SHS field HA761. Only the brightest component was previously identified as Brand 152, a nebula of unknown nature (Brand, Blitz & Wouterloot 1986). The new SHS imaging reveals further and much more extensive structural information that indicated it might be an SNR candidate worthy of spectroscopic follow-up. There is a strong morphological similarity between this object and known Galactic SNR IC 443.

From SIMBAD there are no pulsar, X-ray or radio sources catalogued in the immediate vicinity. However, a separate check against existing radio survey data reveals a match of radio contours from

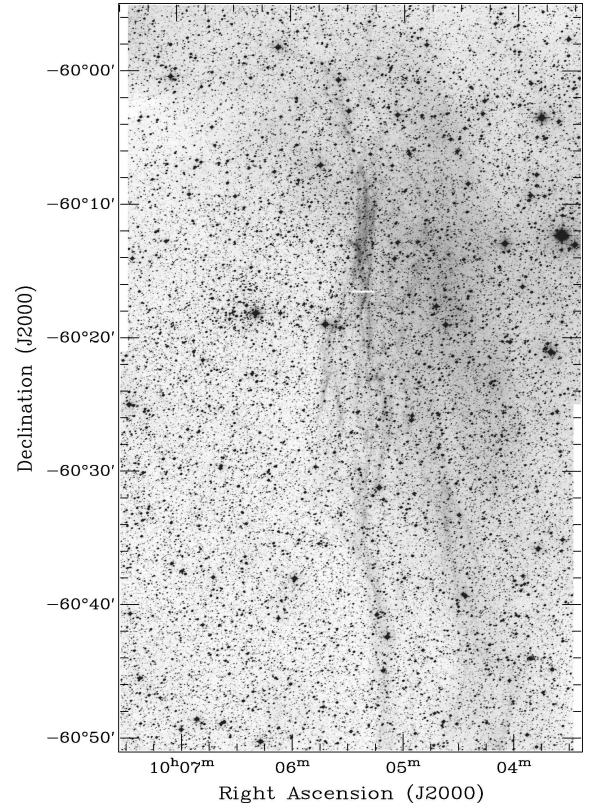


Figure 3. G283.7–3.8. H α high-resolution mosaic image ($\sim 1^{\circ} \times 0.5^{\circ}$) of the most prominent part of G283.7–3.8 showing parallel filaments with maximal extent of 2° . Three SAAO spectra (two low resolution and one with medium resolution of 1200 lines mm⁻¹) confirm that G283.7–3.8 as a likely SNR.

the VLA NVSS 1.4 GHz with the optical image (Fig. 2). The radio contours are fractured but they clearly follow the optical arcuate structure. This is an excellent example of how the existing fractured radio data make it hard to pick up the candidate from the radio data a priori but how easy it is to make the connection once combined with the new H α imaging. This object is situated at the extreme north-west edge of the Gum nebula. The similarity of certain structural aspects and close proximity to this enormous structure cannot rule out that this candidate is connected with this large nebula. However, projection of this new SNR across this part of the Gum nebula is also possible. Support for this conclusion comes from the work of Brand et al. (1986) where this object is also taken to be separate from the Gum nebula. Follow-up spectroscopy shows strong lines of [S II] with [S II]/H $\alpha \sim 0.89$ and very strong H β and [O II] at 3727 Å.

G283.7–3.8. This object comprises a significant group of parallel filaments (Fig. 3) with a maximum extent of 2° and was discovered on SHS field HA174. There is a Wolf-Rayet star WR 17 (HD 88500) (van der Hucht 2001) at RA = $10^{\text{h}}10^{\text{m}}31^{\text{s}}.92$ and $\delta = -60^{\circ}38'42''.40$ (J2000.0) about 40 arcmin east from the filaments. The high-quality SHS imaging reveals further structural detail indicating the filaments are unrelated and different in type from the morphological structure of the WR star's nebulae so we do not consider G283.7–3.8 to be an outer, very distant part of the WR nebula but a new SNR candidate. Spectroscopy across three of these filaments confirms this, with [S II]/H α giving a consistent, very high ratio of between 1.2 and 1.8 despite the distance between

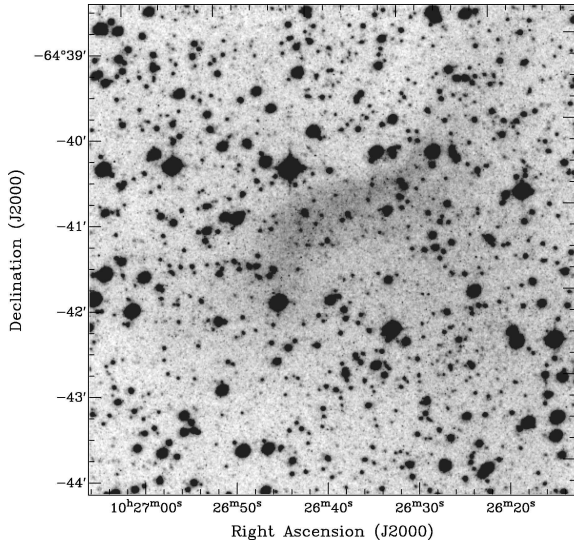


Figure 4. A small $H\alpha$ nebula marked as G288.7–6.3, approximately 2.5 arcmin at maximum extent.

the slit separations of $\sim 1^\circ$. Filaments were observed at the same position with both the low (300 lines mm^{-1}) and high (1200 lines mm^{-1}) resolution gratings with the red spectrum ranging from 6150 to 6900 Å. The spectra exhibit characteristic SNR optical emission lines including extremely strong $[\text{O II}]$ at 3727 Å. The $[\text{O III}]$ lines at 4959 and 5007 Å are also present.

SIMBAD did not reveal any catalogued pulsar, X-ray or radio source in the vicinity and inspection of the PMN and SUMSS surveys did not give any significant radio detection though this may be due to radio dish insensitivity to such large structures.

G288.7–6.3. This optical $H\alpha$ nebulosity (see Fig. 4), about 2.5 arcmin at maximum extent, was discovered on SHS field HA132. This nebulous patch matches the north-west part (see Fig. 5) of the candidate SNR G288.7–6.3 (Duncan et al. 1995) so it is reasonable to conclude that this nebulosity may represent the first detected optical counterpart of this candidate SNR. SIMBAD did not confirm the existence of any catalogued objects at the position of the neb-

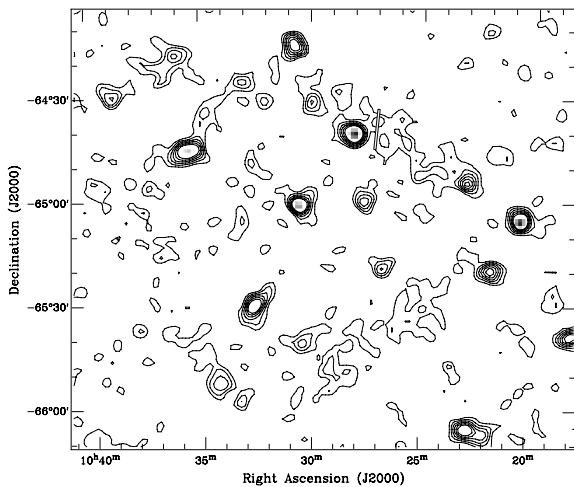


Figure 5. G288.7–6.3 candidate SNR from Duncan et al. (1995) at 4850 MHz (PMN) with contours from 0.01 to 0.06 Jy beam^{-1} . A black rectangle marks the position of the slit against the distinct radio shell morphology.

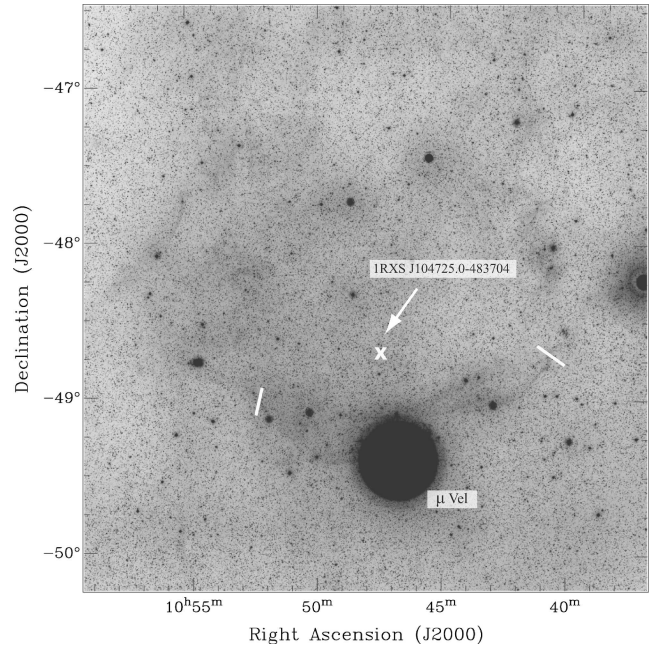


Figure 6. G281.9+8.7 and G283.7+9.3. The faint, oval structure is ~ 2.5 across at maximum extent as seen on $H\alpha$ survey field HA335. Two white bars, G281.9+8.7 and G283.7+9.3 show the position and orientation of the spectrograph slits separated by ~ 1.5 which yield a strong similarity in the observed spectra. The line ratios confirm that they are both likely part of the same object. The white cross gives the position of *ROSAT* X-ray source 1RXS J104725.0–483704.

ulosity, but did return 9 X-ray sources inside the larger candidate G288.7–6.3 (which has an overall radio extent of $\sim 2^\circ$).

The medium dispersion 2.3-m spectrum taken shows reasonable SNR spectral characteristics with the ratio $[\text{S II}]/H\alpha = 0.54$. Such values have been known as upper values for some H II regions (see discussion in Fesen et al. 1985). The ratio of $[\text{N II}]/H\alpha$ is also low which although not ruling out an H II region identification and the value is at the lower level found for SNRs, but is still in accordance with different abundances of nitrogen inside the Galaxy. In the 2.3-m blue spectrum however extremely strong $[\text{O II}]$ emission at 3727 Å is seen together with prominent $[\text{O III}]$ at 5007 Å (359 and 91 against $H\beta$ is seen), which effectively eliminates an H II region but not a PN.

G281.9+8.7 and G283.7+9.3. This is a faint, large, oval structure ~ 2.5 across at maximum extent discovered on SHS field HA335 (see Fig. 6) by Parker and Frew during searches for evolved planetary nebulae (e.g. Frew, Parker & Russell 2006). The coherent $H\alpha$ morphology indicates a possible SNR candidate. Follow-up spectroscopy was undertaken at locations indicated in the Fig. 6 by white bars.

Extremely high ratios of $[\text{S II}]/H\alpha = 3.8$ and 3.4 were found in the red spectra at the two slit positions which are 1.5 apart indicating highly shocked gas, which, given the extent of the source, strongly suggests an SNR origin. Prominent $[\text{O II}]$ at 3727 Å and the presence of Balmer lines $H\beta$, $H\gamma$ and $H\delta$ in the blue were found.

SIMBAD returned a few X-ray sources within the area, but the *ROSAT* source 1RXS J104725.0–483704 is located directly in the centre of the oval structure. Unfortunately, the available PMN and SUMSS data do not show any discernable radio structures.

G288.3+4.8 and G288.7+4.5. A complex of two main arcuate filaments about 15 and 5 arcmin at maximum extent were

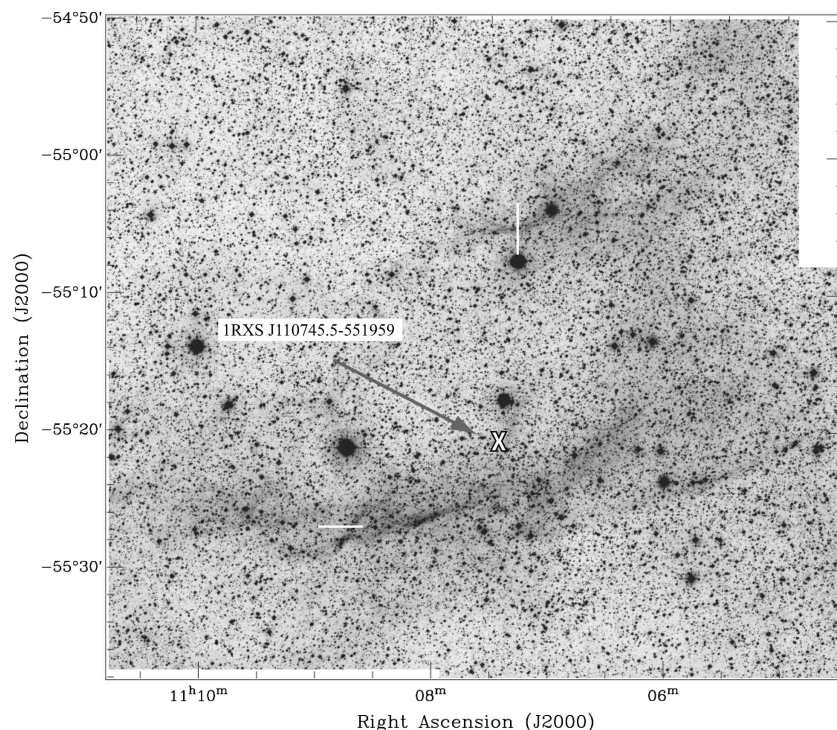


Figure 7. G288.3+4.8 and G288.7+4.5. Mosaic image (48×48 arcmin 2) of G288.3+4.8 and G288.7+4.5 built from the three high-resolution images from H α survey field HA224. Two arcuate filaments some 5 and 15 arcmin in extent are clearly seen. Approximate slit positions are also marked. The white $\times$ mark indicates the position of the *ROSAT* X-ray source 1RXS J110745.5–551959.

discovered on SHS field HA224. A faint background nebulosity also seems to connect these filaments (Fig. 7) on the western side and extend to the north some 7 arcmin from the smaller arcuate filament. One spectrum per filament was obtained using the MSSSO 2.3-m telescope. Both spectra exhibit typical SNR characteristics with strong [S II] emission. In the blue spectra, prominent Balmer lines of H β , H γ , H δ are seen together with strong [O II] at 3727 Å which also support an SNR classification. The absence of [O III] at 4959 and 5007 Å clearly rules out a PN.

Inspection of the PMN and SUMSS surveys did not reveal any significant radio detection though SIMBAD did return an X-ray source 1RXS J110745.5–551959 (see Fig. 7) located 5 arcmin north from the central region of the larger arcuate filament. A more detailed radio study at high sensitivity is required.

G289.7+5.1. A large, faint group of arcuate H α structures was discovered on SHS field HA224 (Fig. 8) where the largest filament is about 22 arcmin at maximum extent. MSSSO 2.3-m blue and red spectra were obtained along the smaller arcuate 7 arcmin filament seen on the western side of Fig. 8. The flux calibrated red spectrum exhibits strong [S II] with [S II]/H α ~ 1.4 while the [O I] lines at 6300 and 6364 Å are seen in the expected ratio 3:1, confirming very good sky subtraction in this decent S/N spectrum. In the blue spectrum, extremely strong H β and [O II] at 3727 Å was seen and, as is sometimes present in SNR spectra, [Ne III] + H at 3970 Å.

The PMN 4850-MHz radio survey data show a clear radio detection (Fig. 8). The radio contours (at maximum 0.06 Jy beam $^{-1}$) concentrate around and are aligned with the western 7 arcmin optical filament where the spectrum was taken and also around the longest, 22 arcmin long filament. No concentration of radio emission at 4850 MHz has been noted in the area of the third, 15 arcmin filament, seen on the north-east side of Fig. 8.

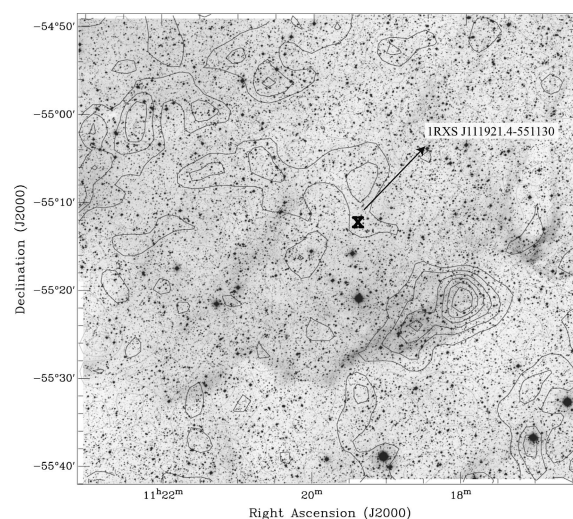


Figure 8. G289.7+5.1. A $\sim 1^\circ$ H α high-resolution mosaic field of G289.7+5.1 with the H α image overlaid with PMN 4850-MHz contours in the range 0.01–0.06 Jy beam $^{-1}$. Three filaments 22, 15 and 7 arcmin in extent are clearly seen. The white $\times$ sign marks the position of X-ray source 1RXS J111921.4–551130.

A SIMBAD search returned the X-ray source 1RXS J111921.4–551130 located between three filaments which is marked as a ‘cross’ ($\times$) on Fig. 8.

G289.2+7.1. This is a large, prominent, arcuate filament about 30 arcmin in maximum extent and was discovered on SHS field HA278 (Fig. 9). The area some 2° around G289.2+7.1 is rich with filaments of different size and form, but this particular arcuate

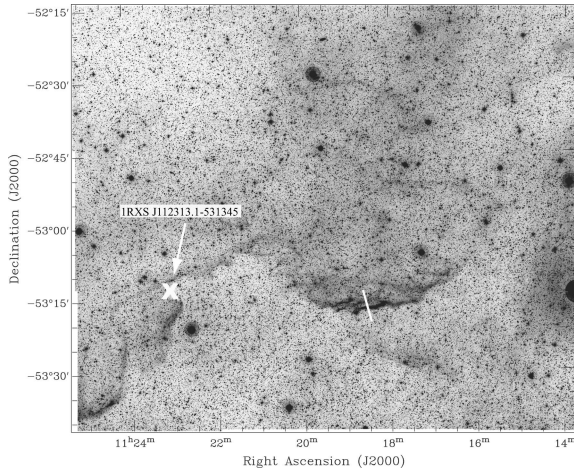


Figure 9. G289.2+7.1. High-resolution mosaic image of G289.2+7.1 built from 12, 30 × 30-arcmin² high-resolution SHS images. The slit position of G289.2+7.1 was almost perpendicular to the 30-arcmin filament front shock. Faint ‘trailing jets’ can be seen behind this front shock which is common in some remnants. Again the × sign marks the position of the *ROSAT* X-ray source 1RXS J112313.1–531345.

filament is very prominent and has a strong morphological similarity to SNRs. Behind the arcuate shock front, is a faint trailing or ‘jet’ nebulosity (Fig. 9). One red and blue spectrum, with slit position almost perpendicular to the observed shock front was obtained with the MSSSO 2.3-m telescope. The red spectrum exhibits typical SNR spectral characteristics with [S II] $H\alpha \sim 1.8$ and with [O I] at 6300 Å. In the blue [O II] at 3727 Å is seen. Inspection of PMN and SUMSS surveys gave no detectable, coherent, radio emission.

SIMBAD returned an X-ray source 1RXS J112313.1–531345 (Fig. 9) located some 30 arcmin from the east boundary of the arcuate filament where the spectra was obtained but any association seems tenuous.

G292.9+4.4 (RCW 59). This is a very large, prominent, oval nebulosity (Fig. 10) previously known as H II region RCW 59 (Rodgers et al. 1960) located on SHS field HA225. The sensitivity of the SHS is able to reveal the full extent of this object which is now shown to be about 100 arcmin in diameter.

In the radio, SUMSS at 843 MHz covers this area, but it is not yet in the public domain. The available PMN data contoured in the range of 0.01–0.07 Jy beam^{−1} reveal fractured structure but with an excellent match to the $H\alpha$ emission (see Fig. 10). The PMN contours continue at the same level over the south-west arcuate structure of RCW 59, where the level of $H\alpha$ emission is very low so effectively forming a complete ring of low level radio emission.

Due to the large extent of this arcuate nebulosity, SIMBAD returned more than 15 X-ray sources in the area, so it is not straightforward to deduce if any are connected with RCW 59. One pulsar, J1132–5627, is situated in the north-west arc of RCW 59.

The new MSSSO 2.3-m blue and red spectra exhibit typical SNR characteristics with [S II] $H\alpha \sim 0.97$ and weak [O III] at 4959 and 5007 Å relative to $H\beta$ (which rules out an evolved PN), $H\gamma$ and $H\delta$, and very strong [O II] at 3727 Å. The N II/ $H\alpha$ ratio is ~ 0.7 at the very upper limit of what is found in H II regions (Fesen et al. 1985). Also in the blue spectrum lines of Ne + H at 3888 Å and [Ne III] + H at 3970 Å are detected which are sometimes present in SNR spectra.

This object was known as a star-forming H II region or possibly part of some larger structure (Avedisova & Palous 1989; Georgelin

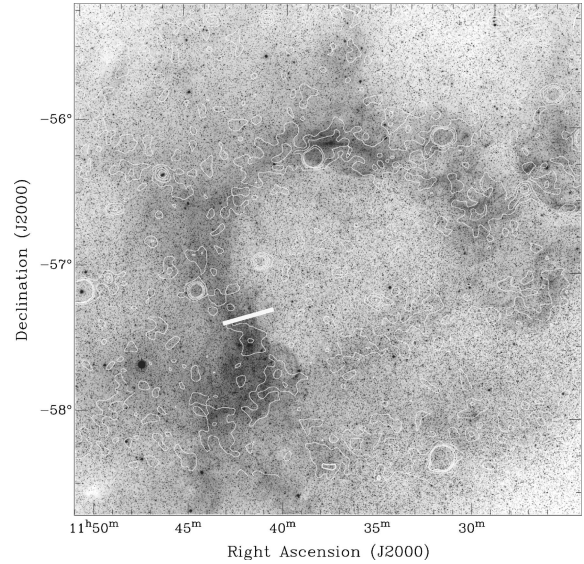


Figure 10. The $H\alpha$ emission of G292.9+4.4 (RCW 59) from the $H\alpha$ survey overlaid with radio contours (0.01–0.07 Jy beam^{−1}) from the PMN survey (4850 MHz). It is clear that the radio data, though fractured, closely follows the arcuate structure seen in $H\alpha$.

et al. 2000), most likely due to morphological similarity of the RCW 59 optical loop with other H II regions. No optical spectra could be found in the literature, so ours is the only existing spectrum. Strong support for reclassification of RCW 59 as an SNR comes not only from this new spectrum and the associated radio structure seen with the PMN but the morphology of the more extensive optical nebulosity now revealed by the SHS. Additional spectra along more of the arcuate structure and especially in the south-east part of RCW 59 (diffuse emission area) are required for a final conclusion about the nature of this object.

The Galactic coordinates presented are for the central area of RCW 59 (from Rodgers et al. 1960) and not coordinates of the slit position as generally given in this catalogue.

G303.6+5.3. This is a large, prominent, oval formation about 4° × 2.5° in extent discovered on SHS field HA228 (Fig. 11). SIMBAD returned two X-ray sources (*ROSAT* 1RX J131108.3–575012 and 1RX J130518.6–575816) in the central area separated by about 45 arcmin. Towards the western edge there is a pulsar J1317–5759 (Fig. 11). These two X-ray sources and pulsar are strongly indicative of an SNR in this region, but further analysis is required to reveal any true connection. More tellingly, the PMN 4850-MHz radio data (see Fig. 11), though fractured, closely follow the oval structure seen in the $H\alpha$ survey. The SUMSS 843-MHz survey data of this region are not yet in the public domain to offer corroboration and an opportunity to measure a spectral index.

MSSSO 2.3-m blue and red spectra have been obtained (see slit position at Fig. 11) which exhibit typical SNR characteristics. In the red spectrum strong $H\alpha$ and [S II] are present with [S II]/ $H\alpha \sim 0.74$. The blue spectrum has strong [O II] 3727 Å and $H\beta$, $H\gamma$ and $H\delta$ Balmer lines. Also, there is weak but clearly present [Ne III] + H at 3970 Å. All these lines sustain the SNR classification.

G306.7+0.5. This is a large, prominent, arcuate nebulosity about 25 arcmin north–south at maximum (Fig. 12) discovered on SHS field HA180. The Wolf–Rayet star (van der Hucht 2001) WR 53 (HD 117297) is about 50 arcmin eastward. At 40 arcmin in the same direction the *ROSAT* X-ray source 1RX J132850–615458

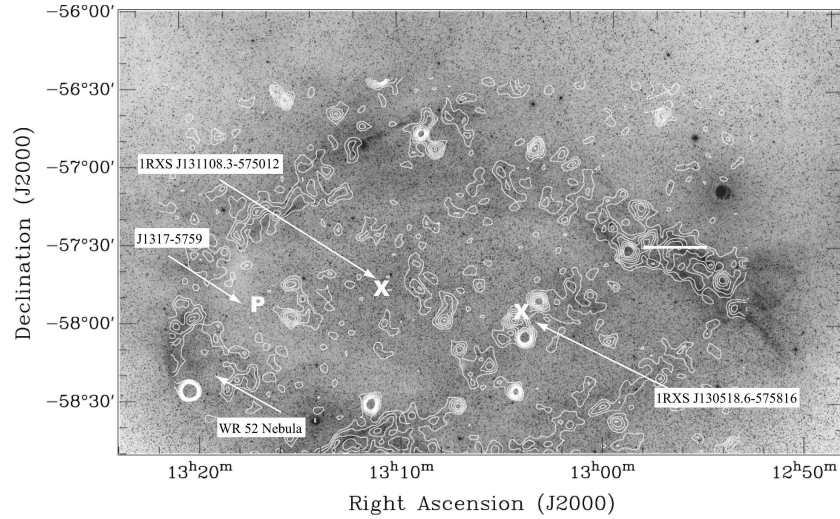


Figure 11. G303.6+5.3. The large H α oval formation $\sim 4^\circ \times 2.5$ in size, with all related objects indicated. The white $\times$ mark the positions of two *ROSAT* X-ray sources while the ‘P’ indicates the pulsar J1317–5759. On the south-east side is marked the Wolf–Rayet star nebula WR 52, evidently not connected with this SNR candidate. The slit position is marked on the west side of the image. The optical oval structure is overlaid with PMN 4850-MHz contours from 0.01 to 0.07 Jy beam $^{-1}$, which, although fractured, closely follows the H α emission.

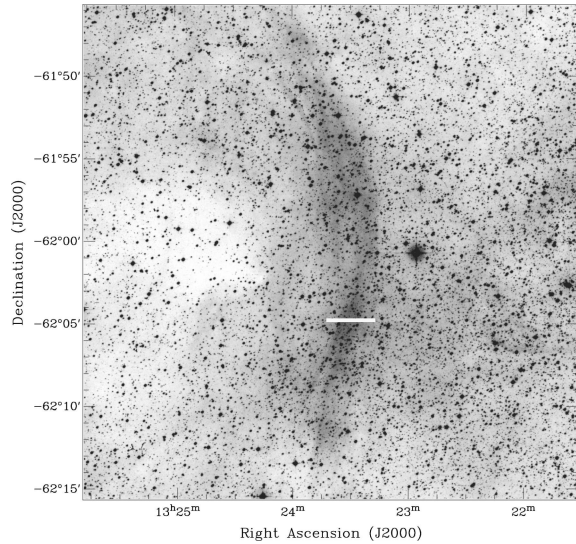


Figure 12. G306.7+0.5. A 30-arcmin SHS H α image of the large arcuate emission structure. The slit position is indicated with a white bar and was oriented east–west at 90° to the filament.

is located and about 3 arcmin further south-east is the pulsar J1329–6158 (see Fig. 13).

Although the area is complex and hard to disentangle the existence of the X-ray source and pulsar and the arcuate structure to the west indicated that the nebula might be part of an SNR candidate worthy of spectroscopic follow-up. Blue and red 2.3-m spectra were obtained. The flux calibrated red spectrum gave $[\text{S II}]/\text{H}\alpha = 0.9$ which is more the signature of an SNR but such large values are not unknown in Wolf–Rayet ejecta. The spectrum also exhibited $[\text{O I}]$ at 6300 and 6364 Å in the expected lock-step ratio of 3:1 while in the blue the presence of all prominent Balmer lines and $[\text{O II}]$ at 3727 Å also support an SNR classification.

Inspection of the PMN 4850-MHz and SUMSS 843-MHz radio survey data shows some very weak radio detection (almost at the level of the noise), so precise details cannot be deduced about the

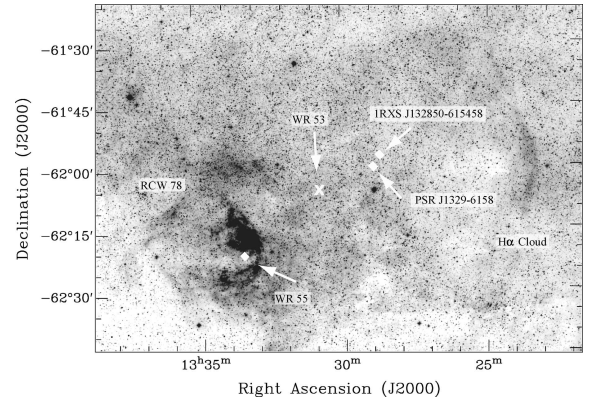


Figure 13. A much larger H α image of the area around G306.7+0.5 showing the position of the X-ray source IRXS J132850–615458 and pulsar PSR J1329–6158. The position of the Wolf–Rayet star WR 53 is also marked as a possible source of the observed H α arcuate nebulousity. The image also shows the position of WR 55 and surrounding nebula RCW 78.

veracity of the radio detections until more sensitive observations are carried out.

G315.1+2.7. This is an isolated, filamentary nebulousity, extending some 11 arcmin in the north–south direction and first seen as an elongated nebular ‘blob’ in the $16\times$ blocked-down fits image of SHS field 231. Examination of the original survey films at ROE showed the fine, twisted structure and full extent of this filament presented at full SHS resolution in Fig. 14.

Investigation showed that this filament is the optical counterpart of a possible SNR candidate G315.1+2.7 identified from previous radio observations (Duncan et al. 1995, 1997). An excellent match was achieved between the optical filament and radio flux contours on the east part of G315.1+2.7, especially with the radio map at 843 MHz (SUMSS) (see Fig. 14).

Optical spectra, taken at two locations along the filament had typical SNR characteristics such as strong $[\text{S II}]$ but with different values of the $[\text{S II}]/\text{H}\alpha$ ratio of 0.8 and 1.5. In the blue, both spectra showed all Balmer lines and $[\text{O II}]$ at 3727 Å. This object, which

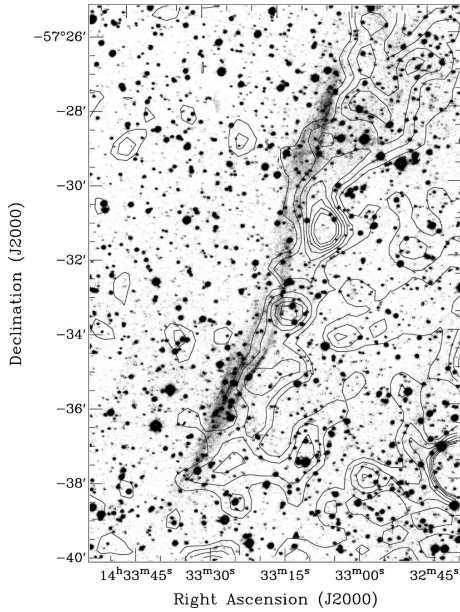


Figure 14. G315.1+2.7 filament as a quotient image ($H\alpha$ divided by the matching short red) overlaid with SUMSS 843-MHz contours from 0.001 to 0.01 Jy beam $^{-1}$. There is clear alignment between the radio and optical emission with a displacement between the radio and optical filament of <1 arcmin.

we now confirm is a bona fide Galactic SNR, forms the basis of a detailed analysis in Stupar et al. (2007a). Representative blue and red spectra across this filament are given in Fig. 15.

G332.4+0.6. This is a large, almost complete ring of $H\alpha$ emission, approximately 30 arcmin in diameter but with a strong, complicating HII region on the north-east side (Fig. 16). It was uncovered on SHS field HA289. The oval form indicated it might be an SNR and a 2.3-m optical spectrum was obtained.

The red spectrum exhibits typical SNR spectral characteristics placing it firmly in the SNR domain. The strong $[NII]/H\alpha$ ratio is also not seen in HII regions while in the blue, the spectrum has low S/N but the only easily recognized line is $H\beta$ so the lack of detectable $[OIII]$ also mitigates against the object being an evolved PN.

A SIMBAD search returned a pulsar J1610–5006 located on the northern limb of this ring nebula. In the radio, the PMN 4850-MHz survey data reveal a striking ring structure which closely follows the $H\alpha$ emission (Fig. 16) though this was not previously identified as an SNR candidate. The south-east part of this structure is without PMN data so confirmation that the radio data completely follow the $H\alpha$ emission is not currently possible. Nevertheless the strong coincidence between the shell-like optical and radio morphology coupled with the highly indicative optical spectroscopy enables identification as a new Galactic SNR.

G343.4+3.6. This object comprises two broad, arcuate filaments (Fig. 17) about 7 and 4 arcmin at maximum extent which were discovered on SHS field HA428. This field contains a significant amount of complex $H\alpha$ emission structures but these stood out as a decent SNR candidate. Low-resolution SAAO 1.9-m spectra (300 lines mm $^{-1}$ covering 3500–7500 Å) were taken across these newly identified filaments.

The spectra do exhibit SNR characteristics. All prominent Balmer lines are registered as well as $[OII]$ at 3727 Å. The lack of $[OIII]$ in the blue mitigates strongly against a PN identification and though $[SII]/H\alpha = 0.6$ is at the lower end of values found for SNRs the

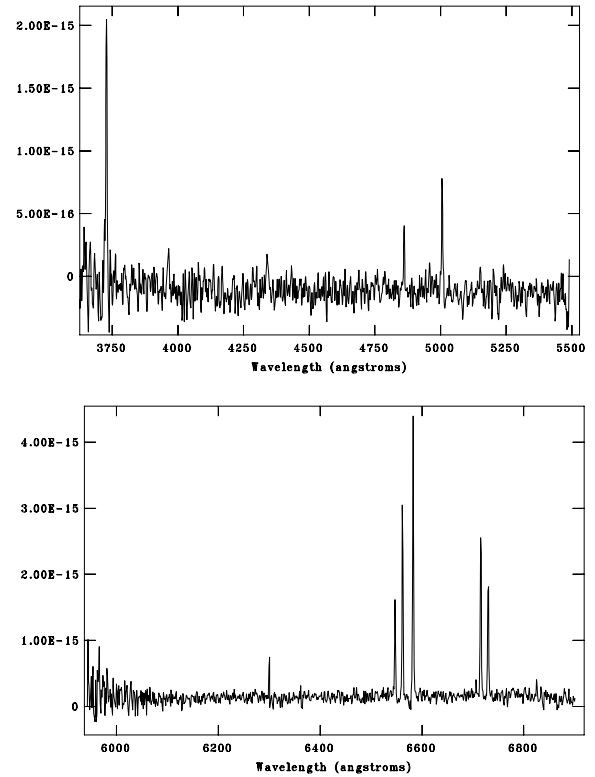


Figure 15. Blue and red flux calibrated spectra for G315+2.7 revealing in the red strong $[SII]$ lines, the strong $[NII]$ relative to $H\alpha$, and the $[OII]$ lines at 6300 Å. The blue spectrum (top image) has the $[OIII]$ doublet at 4959 and 5007 Å showing ~ 200 against $H\beta = 100$.

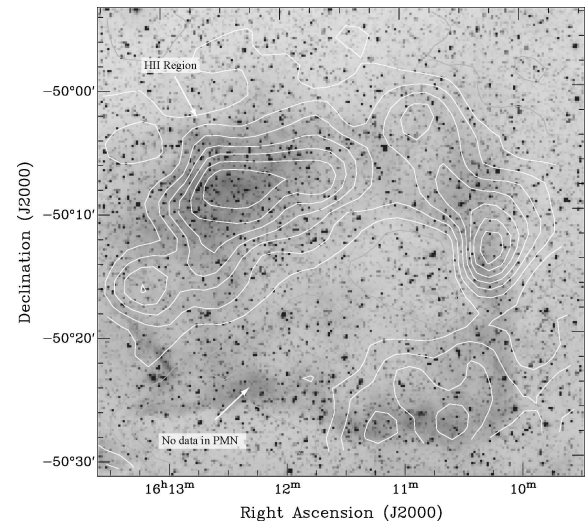


Figure 16. G332.4+0.6 in $H\alpha$ light with overlaying PMN contours (from 0.01 to 0.14 Jy beam $^{-1}$). The unrelated HII region is indicated to the immediate north-east. In the south-east the PMN survey is without data so it is not yet possible to confirm a complete match of the radio and optical emission across the entire ring.

$[NII]/H\alpha$ ratio of 0.8 is greater than that found in HII regions. The spectra were taken on a non-photometric night so the extinction estimates are indicative (extinction coefficient $c = 1.26$) though the $H\alpha$ to $H\beta$ ratio is $\gg 3$ so modest extinction is present.

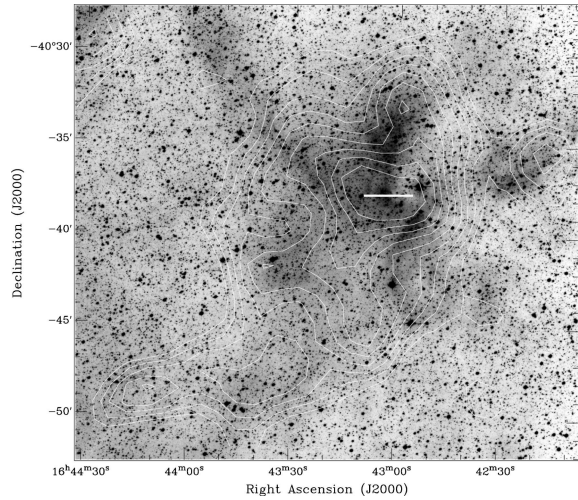


Figure 17. G343.4+3.6 with slit position and PMN contours ($0.01\text{--}0.07\text{ Jy beam}^{-1}$) overlaid on the H α image. Strong correlation between the optical and radio emission is evident.

SIMBAD did not return any interesting objects in the vicinity but inspection of the PMN data does detect the object. Fig. 17 shows the radio contours of $0.01\text{--}0.07\text{ Jy beam}^{-1}$ which closely matches the underlying H α emission making an association highly likely. More precise details are not possible due to the low resolution of the PMN survey (FWHM of 64-m dish was ~ 4.3 arcmin) but the combination of optical spectral properties, elimination of most likely alternatives and matching radio and optical emission permits identification as a probable new Galactic SNR.

G332.5–5.6 – the ‘paperclip’. This SNR was one of the first to be optically detected from the H α survey during a search for PN candidates as part of the MASH project. This remnant was first recognized as a candidate SNR in Duncan et al. (1995) due to its approximately 30 arcmin circular radio morphology. In Parker, Frew & Stupar (2004) we presented the first optical spectra of one of the newly identified filaments of G332.5–5.6 which indicated a likely SNR origin. Full details can be found in Stupar et al. (2007c)

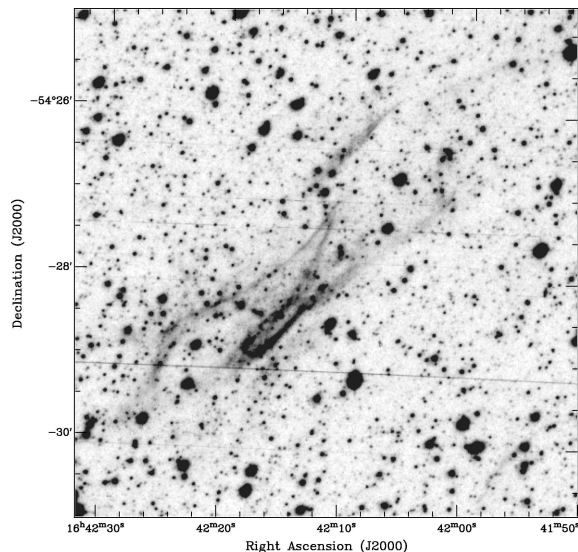


Figure 18. The most prominent optical filament of G332.5–5.6 in the form of a ‘paperclip’. For full details see Stupar et al. (2007c).

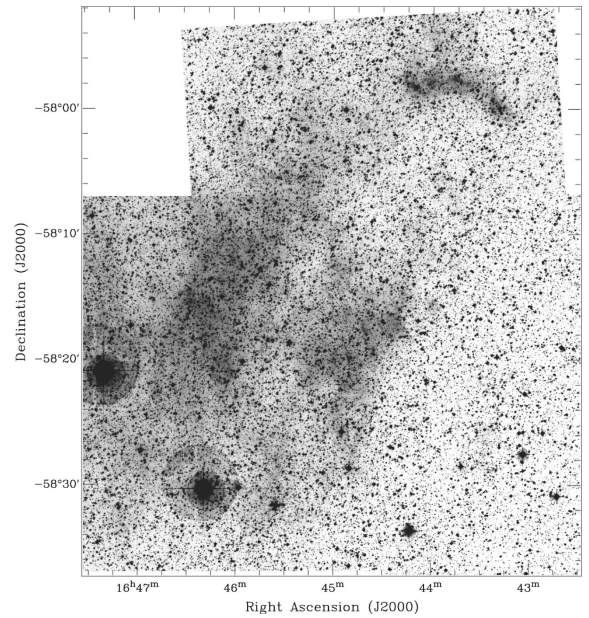


Figure 19. G329.9–7.8. This is the prominent, arcuate nebula at the top right-hand corner of the large 45 arcmin mosaic image. The lower left-hand nebular clouds may represent ‘jet trails’ from the possible SNR shock front.

where the non-thermal nature of this object was confirmed. For convenience and completeness here we present in Fig. 18 an H α image of the brightest optical filament where the nebula has the form of a ‘paperclip’. This object was independently studied by Reynoso & Green (2007) but based solely on radio data though this object was recognized first by our SHS imagery.

G329.9–7.8. This is a prominent, arcuate nebula about 7 arcmin at maximum extent discovered on SHS field HA236. Fig. 19 shows two trailing amorphous ‘jets’ some 10 arcmin behind the main shock front in the south-easterly direction. Typically, these trails, seen in many SNRs, are located right behind the shock front while here they are ~ 10 arcmin behind so a definite connection is not proven. The H α structure indicated it might be an SNR and worthy of spectroscopic follow-up.

An SAAO 1.9-m low-resolution spectra was obtained and the slit position marked on Fig. 19. The spectrum exhibits typical SNR characteristics with $[\text{S II}]/\text{H}\alpha \sim 1.18$ and $[\text{N II}]/\text{H}\alpha \sim 1.8$, effectively eliminating an H II region and PN. $[\text{O I}]$ at $6300\text{ \AA}$ was also present while in the blue strong $[\text{O II}]$ at $3727\text{ \AA}$ is detected, important in aiding SNR classification. The spectrum was taken on a non-photometric night of poor seeing so a formal extinction calculation was not performed though the weakness of H β indicates moderate extinction.

A SIMBAD search did not return any interesting object in this area and nothing was noted in the existing radio data.

G348.2–1.8. This unusual object, discovered on SHS field HA483, is represented by two prominent, parallel arcuate nebulosities (Fig. 20) about 8 and 5 arcmin at maximum extent and separated by about 2 arcmin. One 2.3-m spectrum was obtained for each filament which exhibit typical SNR characteristics with $[\text{S II}]/\text{H}\alpha \sim 0.7\text{--}0.9$ together with H β , and $[\text{O II}]$ at $3727\text{ \AA}$ in the blue part of the spectrum. The $[\text{N II}]/\text{H}\alpha$ ratio from both slit positions varies from 0.8 to 1.1 effectively ruling out an H II region origin.

SIMBAD did not return any remarkable object in this area but the PMN 4850-MHz radio survey data show an object coincident

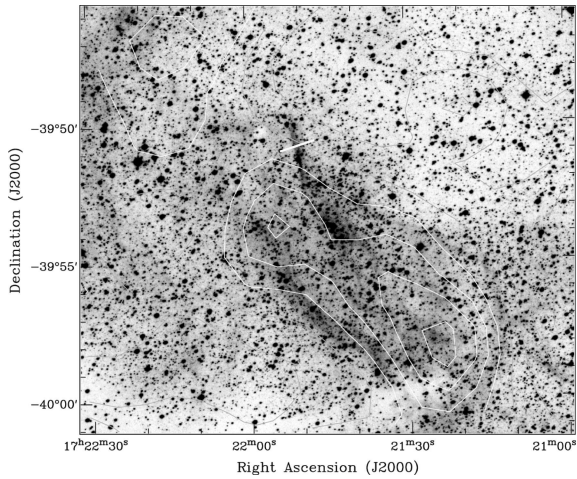


Figure 20. G348.2–1.8, exhibiting two arcuate nebulosities with slit position for the northernmost component indicated by the white bar. The sizes of these parallel nebulosities are 8 and 5 arcmin at maximum extent and are separated by about 2 arcmin.

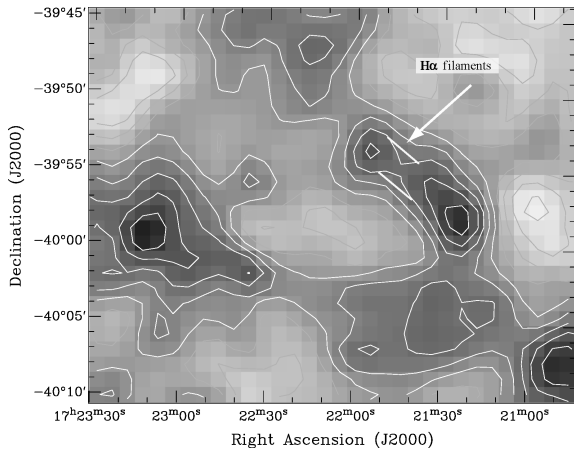


Figure 21. Wider area around G348.2–1.8 with the position of the $H\alpha$ filaments indicated. Without higher sensitivity and improved resolution radio observations, firm conclusions about the connection of the extended radio sources into a coherent shell-like remnant cannot be made but the PMN data are highly suggestive. The PMN data contours are from 0.01 to 0.05 Jy beam $^{-1}$.

with the $H\alpha$ emission with the same orientation and of slighter larger extent at about 13 arcmin. A wider 25×32 -arcmin 2 region is shown in Fig. 21 which reveals a more extensive radio ring indicating that a much larger candidate may be present. This area is not yet scanned by SUMSS while the VLA NVSS 1.4-GHz survey does not show any particular object. More sensitive radio maps of this region are required.

G18.7–2.2. This object was first identified as an extremely large, arcuate filamentary nebulosity about 30 arcmin at maximum extent (Fig. 22) on SHS field HA1060. However, a high-resolution SHS mosaic shown in the left-hand panel of Fig. 22 shows a much wider area, some 2° in extent in declination revealing several large, nebulous regions. To the west is known Galactic SNR G18.9–1.1 which shows up as a compact and intense region of radio emission in the PMN 4850-MHz radio map in the right-hand panel of Fig. 22. This remnant is probably unrelated to the other more extensive, fainter and surrounding radio and nebular structures which show

a high degree of positional coincidence and which we consider to be another, older remnant. There are two parallel radio and optical structures about 45 arcmin in extent. Off the south-east edge of the more southerly structure at nearly right angles is the originally noted north–south filament. The radio structure along this filament is more fractured. The NVSS survey shows no data in this area. It is not possible to yet make a definitive connection between the detached but parallel northernmost nebulous cloud and the connected southern elongated components which lie between $-12^\circ 36'$ and $-13^\circ 57'$. This is where the optical spectra were obtained.

Red and the blue MSSSO 2.3-m spectra were obtained which exhibit typical SNR characteristics with $[S\text{II}]/H\alpha \sim 1.33$. In the blue, the strongest lines are $H\beta$ and $[O\text{II}]$ at 3727 Å but $[O\text{III}]$ at 5007 Å, $H\gamma$, $H\delta$, $\text{He} + \text{H}$ at 3888 Å and $[\text{Ne}\text{III}] + \text{H}$ at 3970 Å are also present. The slit position is marked on Fig. 23. The $[N\text{II}]/H\alpha$ ratio of ~ 0.72 is at the extreme of what has been found in $H\text{II}$ regions and the morphology alone rules out a possible evolved PN. These preliminary optical spectra for one small region of this complex are highly suggestive of an SNR but additional spectra across the filaments are needed for confirmation. An estimate of radio spectral index to reveal the non-thermal nature of the structures would be valuable.

SIMBAD returned some X-ray and PMN point-like sources, as well as pulsars in the area, but due to the large size of this nebulosity it is not yet possible to confidently assign any of these sources to this large remnant.

4 DISCUSSION

4.1 Morphological structure and Galactic distribution of the new remnants

From the 18 new Galactic SNR candidates uncovered in this paper from the SHS and for which strongly indicative spectroscopic confirmation has been obtained, 10 of them have $H\alpha$ emission in the form of a shell (or extended arc; see Table 2). This provides strong, independent morphological support towards their identification as SNRs (Lozinskaya 1992). About 50 per cent of the new remnants also have corroborating radio detections at single and in some case multiple frequencies (e.g. G303.6+5.3, G348.2–1.8; see the catalogue). These radio detections more or less match the optical emission in terms of alignment and extent. For some of them (e.g. G332.5–5.6) non-thermal radio spectral indices are also confirmed. This group of observed, shell-like, optical remnants show breaks in the shell structure due to thermal instability and inhomogeneities of the ISM which is typical for SNRs. Behind the evident shock fronts, some of the remnants (e.g. G243.9+9.8 or G289.2+7.1) appear to possess trailing jets of emission which are also present in some known SNRs. An example of the excellent match in morphological structure of these new shell-like remnants is between new candidate SNR G243.9+9.8 and well-known Galactic SNR IC 443.

It is the SHS imagery which has now enabled an association to be made between new, optically uncovered candidate SNRs and the often weak and fractured radio detections which had previously not been recognized or considered as part of any possible SNR.

The remaining 8 out of 18 SNR candidates do not constitute recognisable morphological structures such as a shell or coherent arc but are just localized emission nebulosities or apparently isolated $H\alpha$ filaments of different sizes. In many cases the full extent of any optical counterpart to these remnants may be hidden by

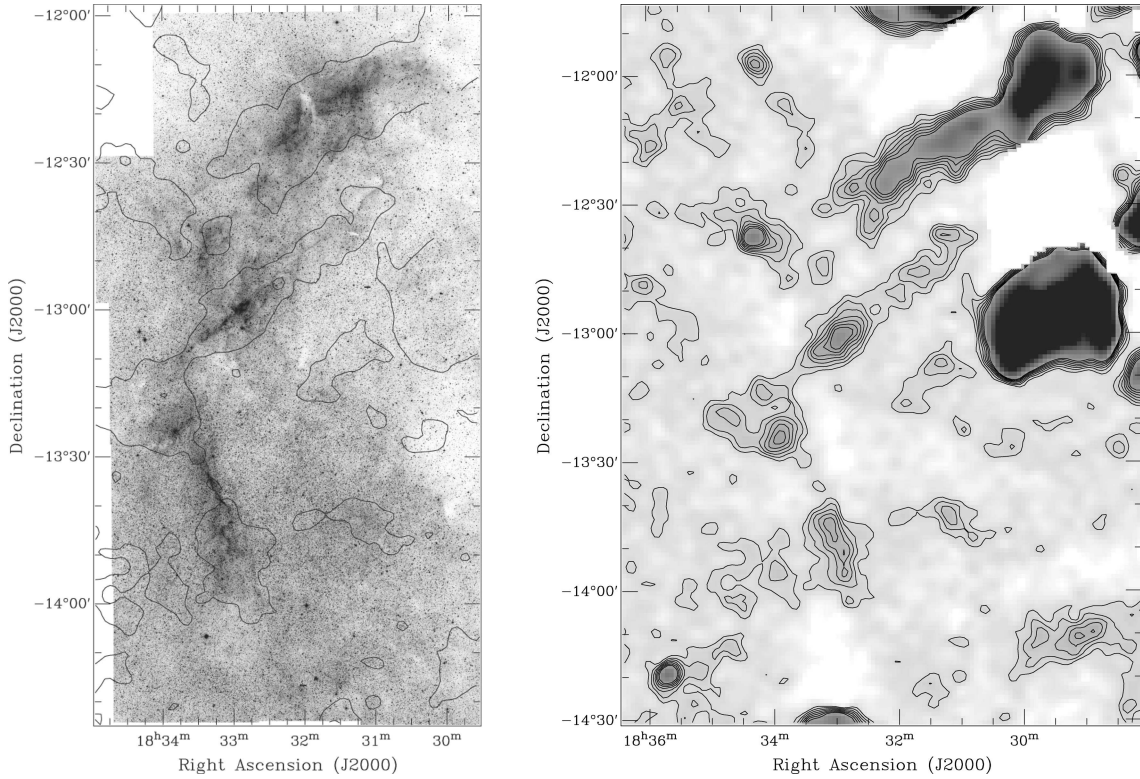


Figure 22. The left-hand image, 2° in extent, is the high-resolution SHS mosaic around slit position G18.7–2.2. The lowest level radio contours of $0.01 \text{ Jy beam}^{-1}$ are taken from the PMN 4850-MHz radio survey. These highlight the excellent match of the radio and optical emission. The right-hand image is a PMN radio image of the same area also overlaid with radio contours from 0.01 to $0.08 \text{ Jy beam}^{-1}$. The southern arcuate nebulosity consists of many PMN point-like sources. The available optical spectra confirm shock excited gas typical for SNRs. The strongest, compact source to the west is known Galactic SNR G18.9–1.1.

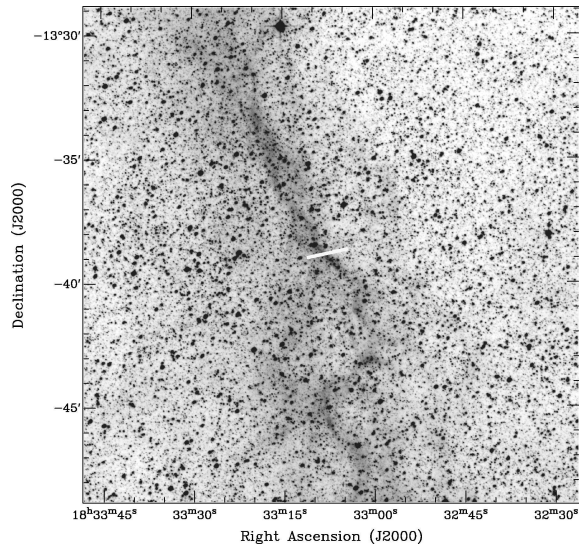


Figure 23. G18.7–2.2. South part the filamentary nebulosity with slit position indicated. It is possible that this is only part of a larger arcuate nebulosity of 1.5° in extent. More spectra are required for a final conclusion.

intervening dust or is not present due to the variable density of the surrounding ISM. Nevertheless, their optical spectra exhibit typical SNR emission lines while other observed line ratios usually rule out H II regions or PNe. Other possible emission nebulae such as Wolf–Rayet shells or Herbig–Haro objects are also easily dis-

Table 2. Morphological structure of the observed filaments.

SNR candidates in the form of shell (or arc)	SNR candidates with irregular form
G253.0+2.6	G283.7–3.8
G243.9+9.8	G288.7–6.3 ^a
G281.9+8.7	G289.7+5.1
G288.3+4.8	G315.1+2.7 ^a
G289.2+7.1	G343.4+3.6
G292.9+4.4	G332.5–5.6 ^a
G303.6+5.3	
G306.7+0.5	G348.2–1.8
G332.4+0.6	G18.7–2.2 ^b
G329.9–7.8	

^aSNR (or candidate) shell in the radio but irregular in the optical. ^bDue to the large angular size, classification is difficult but it could also be considered as part of a very large shell structure.

counted based on environment, morphology and lack of an obvious ionizing point source. This was established after checking known hot star catalogues or from examination of the broad-band colours of stars in the immediate vicinity of the nebulae using the SuperCOSMOS sky survey data (e.g. Hambly et al. 2001) to look for very blue central objects.

Even in cases where the optical emission is patchy or fragmented it still matches equivalent radio emissions when detected (e.g. see G289.7+5.1 and G315.1+2.7). SNR G332.5–5.6 is an excellent example of such fragmented optical filaments which still produce a

good match to the equivalent radio and X-ray data. Together with the optical spectra, a compelling case for SNR identification is made (see also Stupar et al. 2007c).

For some of the newly detected optical filaments, especially those without radio detection (or an X-ray source within the optical emission zone), it is very hard to make any firm conclusion on the true origin of the emission even if their spectra show typical SNR characteristics. There are two possible solutions to what they might represent.

First, they could be the very last vestiges of very old SNRs in the final, dissipation phase where they are almost completely mixed with the ISM. This is all that can be seen for some senile SNRs in the optical (mostly $H\alpha$). No other kind of radiation can be expected (and particularly not in the radio; see later discussion). Secondly, they may form part of a remnant in the snowplow phase and, depending on the nature of ISM (mostly density and temperature) $H\alpha$ radiation can arise. In this case, only fragmented optical filaments in $H\alpha$ may be seen but in the radio (or in X-rays) the whole or partial structure could be expected to be detected (an example is G332.5–5.6).

The diffuse, shell-like, morphological structures, short filaments or small, localized nebulosities, can in principle be present in young as well as in old SNRs. However, based on the overall structure of all 18 observed objects, most are clearly old. Young SNRs, like Cassiopeia A, show very compact and bright (but very complex) shells where inhomogeneities of the ISM cannot have a strong influence in such a very ‘short’ lifetime of a few hundred years. Of course, this is not a strict rule as observed angular ‘compactness’ depends on distance as well as age and, to a lesser extent, also on local, small-scale ISM inhomogeneities.

Many of these new, optically detected SNR candidates are at relatively high Galactic latitudes $|b|$. Only three from 18 candidates have $|b| < 1^\circ$ but essentially the distribution is flat across the SHS full Galactic latitude range out to $|b| \sim 11^\circ$ (see Fig. 24). It is a little surprising more new SNR candidates have not been found closer to the Galactic plane at low latitudes where the concentration of previously known optically detected remnants is higher. Strong extinction clearly plays a role. According to Green (2006), the ratio between objects close to the Galactic plane ($b \pm 1^\circ$) and those with $b > \pm 1^\circ$ is approximately 2.5:1 in favour of remnants concentrated near the Galactic plane.

Another problem for objects at higher Galactic latitude is the contradiction with Kafatos et al. (1980) and the fact that the shock must collide with a dense (~ 0.15 electrons cm^{-3}) ISM in order for

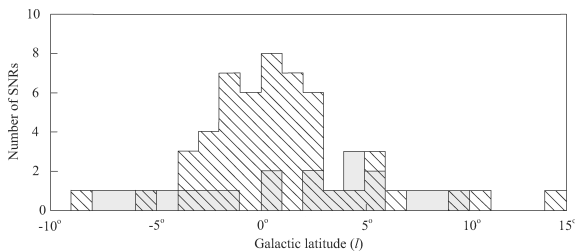


Figure 24. The number of optically detected Galactic SNRs as a function of Galactic latitude (l). The diagonally filled histogram is for the 52 previously known SNRs optically detected and catalogued in Green (2006). The shaded histogram is for the 18 new optically detected SNR candidates discovered in this paper. Green’s histogram shows a concentration of optically detected SNRs around the Galactic plane at low latitudes. There is one previously known optically detected remnant at $l \sim 15^\circ$, SNR G327.6+14.6, (the remnant of supernova 1006) which, as a young remnant, also has published optical observations.

optical emission lines to be detected. There is a concentration of dense clouds around the Galactic plane, with a decrease of ambient density on both sides of the plane with increasing Galactic latitude. Furthermore, Balmer lines, seen in the optical spectra of the entire sample, rise in strength in a high-density environment. At higher latitudes, the ambient density is much lower so the local medium around the newly detected optical remnants must represent an above ambient density responsible for collisional excitation, creation of a shock wave and the Balmer line visibility. Another possibility is that most of these new SNRs are local and so can appear at higher latitudes and still remain within the dust and gas layer. The high sensitivity of the SHS is simply enabling detection of such local, more evolved remnants than before. Independent distance estimates for these remnants is urgently required. The putative Σ – D relation, (Stupar et al. 2007d), does not have the requisite accuracy to clearly solve the ambiguity.

4.2 Emission-line analysis

The detected remnant optical emission lines provide vital clues to their physical nature and a powerful diagnostic capability, e.g. Phillips & Cuesta (1999), Kennicutt et al. (2000) and Reisgo-Tirado & Lopez (2002). Alongside the strength of the $[S\text{II}]$ lines relative to $H\alpha$ the key indicator of SNR shocked material, $[O\text{I}]$ and $[O\text{II}]$ and $[O\text{III}]$ lines are important. The $[O\text{II}]$ 3727 Å doublet is seen in practically all SNR spectra from the sample and is usually very strong in the flux calibrated spectra despite both the poor CCD blue performance and variable extinction giving low S/N shortward of 4000 Å. Only G329.9–7.8 (see Table 3) is without obvious $[O\text{II}]$ at 3727 Å. This non-detection is not definitive since the observations were done under non-photometric conditions and extinction here plays a significant role. When resolved the $[O\text{II}]$ doublet at 3727 and 3729 Å can be used to estimate electron density n_e (Raymond 1979; Osterbrock & Ferland 2006, see also Table 3). The spectral resolution employed in this paper was insufficient to separate these two lines but the $[S\text{II}]$ doublet, which are well resolved and of good S/N can also be used for density estimates (Osterbrock & Ferland 2006).

The oxygen $[O\text{I}]$ lines at 6300 and 6364 Å are usually present in the sample which lends additional support to an SNR classification. However, these lines are also strong in the night-sky spectrum. Hence, given the relatively low spectral resolution and the often highly extended nature of the nebula along the slit (limiting scope for extracting a suitable sky region of sufficient S/N), these lines often suffer imperfect sky subtraction with the expected 6300/6364 Å 3:1 ratio not often observed. The objects are also Galactic so there is no significant velocity difference to offset these lines from the night sky except at higher dispersion. Due to these difficulties these lines were not used in any subsequent analysis. Nevertheless, their obvious detection is a strong supporter of an SNR origin as these lines are rarely seen in $H\text{II}$ regions and weak/absent in PNe, the most likely alternative possible identifications. The $[O\text{III}]$ lines at 4959 and 5007 Å in combination with $[O\text{III}]$ at 4363 Å can provide nebula (electron) temperature estimates with a ratio of 4959 + 5007 Å/4363 Å < 30 regarded as an excellent indicator of an SNR as such a high ratio, indicative of high electron temperatures, cannot be observed in $H\text{II}$ regions or usually PNe (Fesen et al. 1985). However, only 12 objects from the observed candidate sample have detectable $[O\text{III}]$ 4959 and 5007 Å lines with the $[O\text{III}]$ line 4363 Å being far too weak to be detected.

In most cases the 4959 and 5007 Å lines are observed in the expected lock-step ratio of 1:3 but in the case of G281.9+8.7 only

Table 3. Selected physical estimates for the observed sample for every slit position.

Name	Shock velocity V_s (km s $^{-1}$)	Electron density n_e (cm $^{-3}$)
G253.0+2.6	88	181
	100	626
G243.9+9.8	70	–
G283.7–3.8	85	33
	–	129
	82	139
G288.7–6.3	82	760
G281.9+8.7	80	170
G288.3+4.8	50	3.64
G289.7+5.1	50	41
G289.2+7.1	100	139
G292.9+4.4	85	41
G303.6+5.3	50	26
G306.7+0.5	50	74
G315.1+2.7	95	33
	>40	–
G332.4+0.6	70	240
G343.4+3.6	50	83
	110	336
G332.5–5.6	82	227
	98	119
	84	49
	–	400
	–	600
	–	49
G329.9–7.8	80	159
G348.2–1.8	60	57
	40	–
G18.7–2.2	50	92

a weak 5007 Å component is detected due to low S/N. The general weakness of [O III] emission in the candidate remnants compared to strong [O II] 3727 Å rules out the nebula being evolved PNe unless of very low excitation. Furthermore, although the [O III] line at 5007 Å is frequently detected in H II regions, where they are usually weak compared to H β the observed [N II]/H α ratio is usually much greater or at the limit of that for H II regions (e.g. Kennicutt et al. 2000) except for G288.7–6.3 (0.46), G306.7+0.5 (0.55) and G303.6+5.3 (0.58). In the latter two cases the [S II]/H α ratio is also much greater than encountered in H II regions or PNe.

Detection of [O III] 5007 Å is common in SNRs and can be produced in shocks with velocities over 70–80 km s $^{-1}$ (Raymond 1979). This occurs because slower shocks cannot produce doubly ionized oxygen, while those faster than 140 km s $^{-1}$ produce so much H β that the oxygen line becomes relatively weak (Raymond 1979). The [O III] lines observed in SNRs can give us some idea about shock velocities and, when other data and line ratios have eliminated H II regions or PNe, they remain consistent with an SNR identification.

4.3 Estimation of SNR shock velocities

The [O III] 5007/H β ratio was used to provide a shock velocity estimate for the SNR candidates where these lines are seen following Dopita et al. (1984) under the pre-shock physical conditions of 10 cm $^{-3}$ for density, $T \sim 9000$ K and 1 μ G magnetic field strength. This was done when the whole red–blue spectra were available

(SAAO observations), or where only the blue spectra (with both lines) are covered (MSSSO observations). Estimates are in Table 3. Lack of [O III] 5007 Å emission in other remnants suggests shock velocities of 70 km s $^{-1}$ or less. For those remnants the [S II] lines were used for shock velocity estimates. For the SAAO spectra, covering ~ 3700 –7000 Å diagrams adapted from Dopita et al. (1984) were used with [S II] 6731 Å/H α . Where separate blue and red spectra (MSSSO 2.3 m) or where only red spectra (SAAO high dispersion) were obtained, the shock velocity was estimated using the [S II] 6717/6731 Å ratio (Shull & McKee 1979) with pre-shock conditions similar to Dopita et al. (1984).

The shock velocities in Table 3 are only approximate because of the dependence of the shock optical spectrum on shock parameters which is very complex (Raymond 1979). No simple, reliable method is available and many variables are involved such as temperature, density, magnetic field strength, etc. The differences in shock velocity estimates on the basis of line ratios can also be seen in the models of Cox (1972), Raymond (1979), Shull & McKee (1979) and Hartigan, Morse & Raymond (1994).

4.4 Remnant age

The observed [S II] emission-line ratios can indicate whether the remnants are old. Low expansion velocity observed for old remnants have the low-density limit (Daltabuit et al. 1976) while high expansion velocity objects (young remnants) have the high-density limit. The [S II] ratio for young remnants like Cassiopeia A or Kepler’s SNR is typically ~ 0.5 (Peimbert & van der Bergh 1971; Leibowitz & Danziger 1983) while the observed [S II] ratio for this sample is between 0.93 and 1.5, typical for old remnants moving towards the low-density limit.

Apart from the fragmented, faint and large angular size of most of these new optically detected entities, expected for senile, dispersing remnants, additional age confirmation arises because the [S II] ratio can be presented as a function of SNR expansion velocity (Saraph & Seaton 1970; Cox 1972; Daltabuit et al. 1976). For our sample the estimated expansion velocity lies between 30 and 250 km s $^{-1}$ which is typical for evolved SNRs (for an assumed interstellar density $n_0 = 5$). However, for young remnants, this velocity is typically ~ 700 –800 km s $^{-1}$. Hence, these new SNRs are in the snowplow or dissipation phase. Kafatos et al. (1980) state it is easier to observe an optical SNR during its isothermal (cooling) phase than in its adiabatic phase as confirmed here.

5 CONCLUSIONS

Thanks to the high sensitivity and areal coverage of the SHS we have been able to uncover over 80 filaments and coherent nebular emissions over the southern Galactic plane which we deem to belong to new Galactic SNR candidates based on a careful, systematic search of the SHS data. Based on our spectroscopic follow-up of about 60 objects, we have been able to confirm 18 new Galactic remnants comprising 15 new objects and 3 Galactic SNRs previously registered as candidates from existing radio observations. This paper has resulted in an ~ 7 per cent increase in known Galactic SNRs (Green 2006). Significantly, these SNRs have been uncovered via detection of optical H α nebulosities and subsequent optical spectroscopic confirmation rather than from radio observations. Many more candidates await follow-up and confirmation.

Of these remnants 10 have a shell-like structure while the others are isolated filaments or emission clouds. All candidates display typical SNR optical spectra with forbidden lines of [O I], [O II],

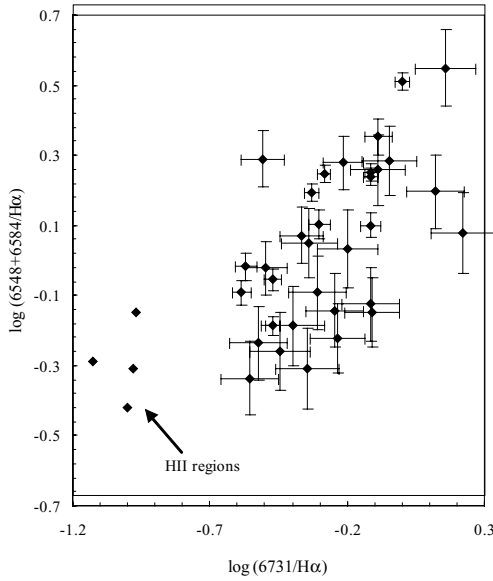


Figure 25. The relationship between $[N II] 6548 + 6584 \text{ Å}/H\alpha$ and $[S II] 6731 \text{ Å}/H\alpha$ established by Dopita et al. (1984), showing abundance-dependent trends. Slight variations in these ratios are primarily due to metallicity changes. Every slit position for each candidate SNR from this paper and line ratios from Table 3 were used in creating this diagram. The arrowed points show typical positions for H II regions taken from Hua & Llebria (1981), Garcia-Rojas et al. (2005) and Garcia-Rojas et al. (2006). All the newly identified SNR candidates fall nicely within the region occupied by SNRs.

$[O III]$, $[N II]$ and $[S II]$, as well as prominent Balmer lines. All the objects have $[S II]/H\alpha > 0.5$ with all but two having this ratio > 0.7 , confirming the presence of strong shock motions typical of SNRs and which clearly separates them from H II regions or most PNe (see Fig. 25). The high $[N II]/H\alpha$ ratio also eliminates these objects as H II regions following Kennicutt et al. (2000).

The only doubtful identification is RCW 59 (or G293.0+4.5 from the slit position), a well-known H II region where the optical structure of the shell is followed in the radio. Only one spectrum was taken of this object but it displays typical SNR characteristics. It is possible that the observed nebula is a mixture of both types of objects. More spectra and detailed radio observations are needed to make a final decision concerning the nature of RCW 59.

All candidate SNRs showed $[S II] 6717/6731 \text{ Å}$ ratios typical of old Galactic SNRs. The $[N II]/H\alpha$ ratio varied between objects, as can be expected due to variations in nitrogen abundance within the Galaxy but with values usually well in excess of those of H II regions. These ratios were also found to vary inside individual filaments (see case of G315.1+2.7) in some remnants an extremely high $[N II]/H\alpha$ ratio was observed (see case of G332.5–5.6). Shock velocity estimates for all candidates were between 50 and 100 km s^{-1} typical for old remnants. Typical SNR electron and pre-shock densities were also observed.

Candidates were checked against existing data from the different radio surveys, i.e. the SUMSS at 843 MHz, NVSS at 1.4 GHz, Parkes at 2.4 GHz and the PMN at 4.85 GHz. Often this led to a fresh evaluation of the radio data and the recognition of clear associations not previously recognized. A check for any possible connection with an X-ray source in the vicinity was also made. 11 objects were shown to have clear positional and feature alignment agreement with

radio sources while 11 objects also revealed a possible connection with X-ray sources.

There remain dozens of SNR candidates we have uncovered that still require spectroscopic follow-up so many additional Galactic SNRs are expected. However, we still need further optical spectra for the SNRs presented here across different parts of each remnant as well as more sensitive multifrequency radio and X-ray observations. Finally, for the first time, we have also optically detected about 30 filaments/diffuse emissions at the positions of known Galactic SNRs (see Stupar et al. 2007b) from the SHS data. According to Green (2006) only ~ 17 per cent of known Galactic SNR had identified optical emission so new detections will shed new light on the optical spectral investigation of Galactic SNRs. We confirm the existence of a new group of SNRs which are radio-quiet but optically active (see Appendix A).

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APPENDIX A: NEGATIVE RADIO DETECTION FOR SOME NEW REMNANTS

A question from this paper is why only some new optically identified Galactic SNRs, based on their morphological and spectroscopic criteria, have not been detected in the available radio surveys? Blandford & Cowie (1982) state that optical emission should have associated radio emission (possibly weak), while clouds, which have been fully crossed by the radiative shocks, may be hardly detected optically. However, we raise the example of G332.5–5.6 the ‘paperclip’ (see Stupar et al. 2007c), where coincident optical, radio and X-ray emission is seen. This raises another problem. The X-ray emission from an SNR must be associated with temperatures of $\sim 10^7$ K. Such high temperatures cannot be connected with cooling shock waves. The explanation is that denser regions, enveloped by the remnant and crossed with a relatively slow, cooling shock, are responsible for the optical/radio detection, while more diffuse gas remains hot and is responsible for the X-ray emission (Blandford & Cowie 1982 on the basis of McKee & Ostriker 1977). Still, the question of missing radio detection remains. We offer several possible explanations.

(i) The search for radio counterparts was made with respect to existing radio survey data whose coverage is far from uniform and samples a broad range of discrete frequencies with widely varying sensitivities and resolutions. Objects may not be seen at a specific frequency, but may be detectable at other frequencies and radio telescope resolutions (see Blandford & Cowie (1982) statement about ‘possibly weak’ radio recognition of remnants). A good example of this is the Vela Z SNR (see Stupar et al. 2005) which is barely on the threshold of recognition at 843 MHz, but is clearly seen at other (higher) frequencies. Also, there is the case of G315.1+2.7 (Stupar et al. 2007a), where a complete shell is seen at 2400 and 4800 MHz, while only one arc is vaguely seen at 843 MHz.

(ii) Another explanation is that some remnants are definitely in the last dissipation phase, almost dissolved and mixed with the ISM. Whether they are truly dissolved, and what might really remain for optical detection, depends on the local ISM density and temperature. For the radio, if the magnetic field in the SNR area comes up to the level of the Galactic background magnetic field, then due to this dissipation, non-thermal emission is not likely to arise and radio detection is not possible. If a light trace of non-thermal radiation exists, then this might only be for small filaments. We need much better resolution radio telescopes to investigate this further such as the future Square Kilometre Array (SKA).

(iii) The model of Blandford & Cowie (1982) predicts the existence of a class of ‘radio-quiet’ remnants which possibly lie at the lower end of the range of surface brightness (radio) at a given remnant radius. This is precisely the regime of these new remnants. This sustains our observations and our statement that we need better resolution radio telescopes as well as more sensitive optical narrow-band surveys. As an example in Stupar et al. (2007b) we report on the first optical H α detection of about 30 known Galactic SNRs recorded in the comprehensive compilation of Green (2006) and identified in the AAO/UKST H α survey (Parker et al. 2005). This demonstrates what is possible with new surveys with improved sensitivity, resolution and wide area coverage.

(iv) Our observations fit the model of Asvarov (2006) where it is clear that the process of generating new radio-emitting electrons

stops with the beginning of the radiative cooling of an SNR. According to Asvarov (2006) these radio-quiet SNRs (with decreased activity in X-rays also) evolve in the homogenous ISM and should emit in the optical and H I wavelengths which is exactly what we are proposing for many of our evolved remnants.

(v) One final support for our SNR identifications, especially in those cases where there are no detected X-ray sources in the vicinity, comes from the recent work of Pannuti, Schlegel & Lacey (2007). They presented a Chandra search for X-ray counterparts of extragalactic SNRs in M 81, M 101, NGC 2403, 4736 and 6946. They used a sample of 138 optically identified SNRs and 50 candidate radio SNRs and found X-ray detection in only nine optically identi-

fied SNRs and in only 12 radio SNRs that were not already known to be time variable or associated with X-ray binaries. They argue that the role played by ambient density seriously affects searches for SNRs in those nearby galaxies at multiple wavelengths. They also conclude that the local environment in which a particular SNR is propagating plays a very important role together with other selection effects such as SN type and survey sensitivity. In another words, they found in external galaxies exactly what we have found for our Galaxy with senile remnants.

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