Filamentary Shell Structures from the AAO/UKST Hα Survey

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Abstract: Here we present the first results of a search for new optical supernova remnant candidates and other filamentary objects on films produced by the Anglo-Australian Observatory/UK Schmidt Telescope Hα Survey. Thirty-nine fields, or 26% of the Galactic plane survey fields, have been visually examined. This has resulted in the detection of four new large diameter filamentary structures, and the discovery of extensive new optical emission in two previously known optical supernova remnant candidates.

Keywords: surveys — ISM: general — supernova remnants — [H]α regions

1 Introduction

Extensive radio surveys within our Galaxy have led to the discovery of 225 supernova remnants as of August 2000 (Green 2000). Of these a small number, including the Crab and Vela remnants, optically present us with a beautiful and complex picture of how the shock wave of a supernova interacts with the surrounding interstellar medium. By examining closely the relationships between the emission seen in different wavelengths, we can obtain a good picture of the processes occurring within the remnant. Most SNRs have been detected through their radio emission, optical counterparts are hard to find because of extinction.

Hα emission from gas in our Galaxy provides us with a picture of how the interstellar medium is being influenced by stars. This gas may be excited in a number of ways, chiefly by the radiation from hot stars, or the passage of shock waves from supernova explosions or strong stellar winds. The nebulae observed in Hα emission have a wide variety of morphologies. The emission may be diffuse, as seen in the Rosette Nebula, or filamentary, as seen in the Vela SNR. Partial or full shell structures are also often seen. Filamentary shell structures, the focus of this work, may be produced by Wolf–Rayet stars, Of and O(f) stars, the central stars of planetary nebulae, and by supernova explosions.

All known optical SNRs, apart from the oxygen rich line (Weiler & Sramek 1988), emit in the Hα line, as well as the [N ii] 6548, 6583 Å lines. These are produced in regions behind the shock front, due to post shock cooling of the excited gas. The Hα survey will cover these lines and is well suited for SNR searches.

The AAO/UKST Hα Survey (Parker, Phillips & Morgan 1999) has the potential to reveal fainter filamentary emission at a higher resolution than previously possible in a wide-field survey. This will improve our knowledge and understanding of optical SNRs and other filamentary structures such as Wolf–Rayet shells by increasing the number and variety available for further study. We have recently commenced two projects. The first, the subject of this paper, is to visually examine survey films to discover new objects classifiable as SNR candidates based on their optical morphology, along with other shell structures. The second is to examine fields of known radio SNRs for optical emission (Walker & Zealey 1998).

Previous SNR searches have concentrated on known objects identified in other wavebands. This work covers the entire southern Galactic plane out to |b| = 10° for the first time optically. The use of Tech Pan film and the Hα interference filter allows the detection of finer and fainter detail than any previous large area search (Parker & Phillips 1998).

In order to ensure completeness of any SNR survey, future optical and radio searches will need higher sensitivities, and will need to be responsive to a wide range of angular scales, from sub arcsecond to several tens of degrees. The Hα survey goes some way to meeting these requirements for our local region out to 4–5 kpc. Optical detections combined with radio observations will provide a more detailed picture of the nature of these objects.

1.1 Wind-blown Shells and Planetary Nebulae

Two hundred and twenty-seven Wolf–Rayet stars are known within the Galaxy (van der Hucht 2000). These hot, massive young stars have broad emission lines in their spectra from Hα and He i, along with various lines from excited states of carbon, oxygen and nitrogen. Of and O(f) stars are massive O stars which also exhibit a range of broad and narrow emission lines. Both of these types have strong stellar winds, typically v = 10¹⁻⁴ × 10⁶ km s⁻¹ and M = 10⁻⁶ – 10⁻² M⊙ yr⁻¹ (Lozinskaya 1992). The stellar wind interacts with the surrounding ISM, which will include matter previously ejected by the star. Optical ring structures resulting from this interaction...
They may be visible for a few times 10^5 years. The largest are under 1 \, \text{AU} producing filamentary shell structures in optical emission. Driven by the stellar wind, these nebulae may expand to over 100 pc in size. Those observed in our Galaxy are mainly between 5 and 20 pc in size (Chu 1992). Their angular diameters vary from a few arcminutes to a few degrees.

Planetary nebulae may also exhibit filamentary structure. Some of their main properties of relevance here are widely varied morphologies; spectra similar to H II regions; hot, low mass central stars, mainly O-type stars; O stars, and Wolf-Rayet stars; and a size of \sim 0.8 pc (Kaler 1985; Kitchin 1987). Their progenitors are normally evolved asymptotic giant branch stars. The largest known planetary nebula, the Helix Nebula, is 15\degree in diameter. However, the majority of the known are under 1\degree in size. All of the objects presented in this work are of a larger size and are not planetary nebula.

A search for planetary nebulae using an Hα survey is being undertaken by Parker et al. (1999) in the Galactic plane. So far they have discovered over 700 candidates from 50% of the survey. Confirmatory spectroscopy has already been obtained for over 300 of these.

1.2 Supernova Remnants

Supernovae result from the core collapse of stars more massive than \sim M_\odot (types Ib, II), or the explosion of a white dwarf due to accretion leading to the star exceeding the Chandrasekhar limit (type Ia). Material in the surrounding ISM is heated by the expanding shock wave producing filamentary shell structures in optical emission. They may be visible for a few times 10^5 years. The largest of these are over 100 pc in size. A summary of the physical parameters of several well studied optical SNRs in our Galaxy is given in Lozinskaya (1992).

The optical morphology and spectra of known SNRs show a great variety of types which depend on:

- the type of supernova outburst
- the influence of any stellar remnant
- the nature of the surrounding ISM
- a contribution from circumstellar material from the progenitor star
- the evolutionary stage of the remnant

Mathewson et al. (1983) have shown from a study of SNRs in the Magellanic Clouds that they can be separated into four classes: Balmer-dominated, oxygen-rich, plerionic-composite, and evolved, that we detail below. Weiler & Sramek (1988) propose a fifth class, centrally-influenced. Details on individual objects may be found in Lozinskaya (1992) and Green (2000).

The Balmer-dominated remnants of Tycho, Kepler, and SN 1006 are believed to result from type Ia supernova, however the Ib class cannot be ruled out. Their spectra are strong in the hydrogen Balmer lines, but weaker in [S II], [N II], and [O III] than the typical evolved case. This results from a non-radiative shock meeting partially neutral gas (Chevalier & Raymond 1978).

Oxygen-rich remnants are distinguished by the presence of filaments with strong [O III] lines and, in many cases, lines of neon, argon, and sulphur. The most studied example is Cassiopeia A; the spectra of its fast moving knots vary widely from feature to feature (Chevalier & Kirshner 1979). This material is ejecta from the explosion of a massive star, most probably within the last 2000 years (Lozinskaya 1992). Other examples are G292.0+1.8, Puppis A; N132D and 0540-69.3 in the LMC; 1E 0102.2-7219 in the SMC; and an unresolved source in NGC 4449.

Plerionic and plerionic-composite remnants are classified as having filled-centre radio emission with a flat spectral index. Plerion-composite remnants have in addition an outer shell with a steeper spectral index (e.g. Weiler 1983; Weiler & Sramek 1988). The main examples of the plerion class are the Crab Nebula and 3C 58 (SN 1181). Vela XYZ and W 28 are plerionic-composites. Many of these have been shown to be strongly influenced by a pulsar, which may be true for the class as a whole. Optically these two classes display extended and filamentary emission throughout their centre.

The evolved remnants encompass the majority of known SNRs and may represent the final state of the other younger classes. They exhibit clear shell structure in the optical and radio, and their optical spectra are dominated by Hα, [S II], and [N II] emission, produced by cooling behind the shock front. One of the best studied objects of this class is the Cygnus Loop.

1.2.1 Previous Optical SNR Searches

The most recent catalogue of Galactic SNRs (Green 2000) presents information on 225 SNRs. Of these 156 are located in the southern sky. Optically, 20 of these SNRs have been detected in the southern sky compared with 31 in the northern sky. The smaller ratio in the southern sky is due to greater obscuration. By making deeper observations a greater proportion of these southern SNRs should be optically visible.

The first known SNRs were the brighter and closer objects such as the Crab and Vela remnants, of which several had obvious optical counterparts. Great advances in the sensitivity and resolution of radio surveys, especially in the late 1960s and more recently using interferometers, e.g. the Molonglo Observatory Synthesis Telescope (MOST) (Whiteoak & Green 1986), has resulted in most objects now being discovered by their radio emission.

Searches have been made to detect optical emission from radio SNRs. The earliest comprehensive work was by van den Berg, Marscher & Terzian (1973) where the 24
then optically identified SNRs are detailed. Further identifi-
cations were made by van den Bergh from the late 1970s
from 1977 onwards, using UKST IIIaF and IIIaJ plates
(Zealey, Elliot & Malin 1979), resulted in the first opti-
cal detection of many southern SNRs. Since then several
other remnants have been optically identified, primarily
through narrow band CCD imaging. References to these
can be found in Green (2000).

1.3 Discrimination between Formation Mechanisms

1.3.1 Optical Morphology as a Discriminator

Optical morphology can provide clues to the origin of fil-
amentary structure, but it is only a guide. The presence
of small knots and condensations, for instance, suggests
ejected material associated with an oxygen-rich SNR, but
this morphology may also be seen in Wolf-Rayet shells
and planetary nebulae. The presence of filaments and dif-
fuse emission throughout the centre may possibly indicate
a plerionic object. Objects seen as partial or complete
shell structures with a large angular size strongly suggest
an evolved remnant. The effects of differing extinction
levels and ISM structure from object to object makes clas-
sification from optical morphology alone impossible. In
general optical spectroscopy, narrow-band imaging, and a
radio spectral index are needed to reveal the true nature of
filamentary objects.

1.3.2 Spectral Discrimination

In parallel with morphology, spectral information from
radio and infrared observations can also be used to dis-
 criminate between the possible sources of the observed
emission. The radio emission of SNRs is produced by the
synchrotron emission of relativistic electrons. This is non-
thermal, and can be fitted by a power law \( S \sim \nu^\alpha \), with
\(-0.8 \leq \alpha \leq 0\) (Lozinskaya 1992). H\(\alpha\) regions have a
thermal spectrum, with \( \alpha \sim 0 \). Separation of the two pro-
cesses can be made by direct measurement of the spectral
index \( \alpha \). Linear polarisation also indicates that the radio
emission is synchrotron.

Better discrimination can often be made by compar-
ing the 60 \(\mu\)m and radio emission from shells. Broadbent,
Osborne & Haslam (1989) have shown a correlation
between IRAS 60 \(\mu\)m emission from the Galaxy and radio
continuum emission. From this it has been shown that the
60 \(\mu\)m to radio flux density ratio is high for H\(\alpha\) regions
and low for SNRs, with both types being well separated. This
method has been used with great success (e.g. Whiteoak &
Green 1996) to identify SNR candidates.

2 The UKST H\(\alpha\) Survey

The H\(\alpha\) survey began in July 1997 on the UKST. Using
4° fields, 233 fields will cover the southern Galactic plane
to a latitude of \( \pm 10^\circ \), and 40 will be used for the
Magellanic Clouds. Each exposure uses a 356 \(\times\) 356 mm
glass H\(\alpha\) interference filter with a central wavelength
of 6590Å and a FWHM bandpass of 70Å. Although
6.5° \(\times\) 6.5° is imaged on each film, the filter is optimal
within a circular diameter of 5.5°, and hence the usual
5° fields would not provide full coverage in the survey
area. The three-hour exposures are taken on Tech Pan film,
which offers improved sensitivity at the H\(\alpha\) wavelength
and improved resolution in comparison with previous
UKST R band surveys which used IIIaF emulsion. Fur-
ther details of the survey and film are given Parker &
Phillips (1998). The filter is described in Parker & Bland-

In February 1998 we began a systematic search of films
produced by the H\(\alpha\) survey. Films badly affected by trail-
ing, poor focus, weather or other factors have not been
closely examined as they will be repeated at a later date.

After an initial quick look to identify obvious large
emission features, each film was visually scanned using a
wide angle magnifying lens. This involved scanning hor-
izontally across the film, working from the bottom of the
field to the top, and ensuring that each strip overlapped so
that no area was missed.

A wide variety of non-stellar objects are imaged on each
film, primarily galaxies, planetary nebulae, and diffuse
H\(\alpha\) regions. SNRs and Wolf-Rayet shells optically have a
filamentary appearance, and so can in general easily be
distinguished from the above.

Digitised images of each object were then obtained,
using an HP desktop scanner with transparency attach-
ment. Approximate x–y positions of each object were
measured off the film. These were entered into the UKST
program PLADAT to obtain rough RA and Dec values.
Using STScI Digitised Sky Survey images and the Karma
program (Gooch 1996), each digitised image had a J2000
coordinate system attached to it. From this accurate posi-
tions were obtained for each object’s centre and sizes were
determined.

3 Discoveries

The most interesting class of objects identified are those
over 30° in extent, with a filamentary appearance and a
partially annular structure. At 5 kpc these objects would
have diameters in excess of 40 pc. The larger of these are
more likely to be identifiable as SNRs, Wolf–Rayet or stel-
lar wind shells, to be relatively close, and to be identifiable
in other surveys.

From the fields examined so far, six such large objects
have been identified. Two of these have been previously
identified as SNR candidates from their optical emission,
however they have been poorly studied and the H\(\alpha\) survey
has revealed far more extensive emission than previously
recognised. A summary of these objects is presented in
Table 1.

In addition we have identified many faint, isolated
filaments under 10° in extent. Very few are identifiable
with known objects. Unless identified as thermal through
a large infrared flux or their radio spectral index, the
best way of identifying these objects will be through
### Table 1: Filamentary structures

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>G245.9+0.9</td>
<td>08h00m.5s</td>
<td>−28°30'</td>
<td>1°20'</td>
<td>New WR shell</td>
</tr>
<tr>
<td>G296.2−2.8</td>
<td>11h47m</td>
<td>−64°30'</td>
<td>1°</td>
<td></td>
</tr>
<tr>
<td>G304.7−3.1</td>
<td>13h18m</td>
<td>−65°56'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G310.2−2.8</td>
<td>14h20m</td>
<td>−64°45'</td>
<td>1°×1°30'</td>
<td></td>
</tr>
<tr>
<td>G340.5+0.7</td>
<td>16h30m</td>
<td>−44°25'</td>
<td>20'</td>
<td>Possible SNR</td>
</tr>
<tr>
<td>Kes 45</td>
<td>16h56m</td>
<td>−43°45'</td>
<td>1°30'</td>
<td>Possible SNR</td>
</tr>
</tbody>
</table>

Positions given are geometric centres of the observed emission.

3.1 G245.9+0.9

This object is very faint on the original film. Computer enhancement shows a large amount of filamentary structure forming a full shell 1° in diameter (Figure 1). The emission is stronger towards the east. Radio continuum observations with the MOST at 843 MHz with resolution 43''×43'' cosec|δ| detected no significant radio emission from the object. However, it is visible, though faint and fragmentary, in 60 µm images from IRAS (Beichman et al. 1985). From this there is a strong likelihood that the object is an H ii region.

The Wolf–Rayet star HD 65865 lies interior to the shell at 7h59m46s, −28°44' (J2000), which is about 20' from the shell’s geometrical centre. It has the spectral type WN5 and a distance of 4.61 kpc (van der Hucht 2000). This would imply a shell diameter of 107 pc if the shell is produced by this star, which lies within the range of shell diameters expected for Wolf–Rayet stars given by Marston (1997), from 1.3 pc to 180 pc.

3.2 G296.2−2.8

Here a nearly complete shell structure over 1° in diameter is visible (Figure 2). Some very fine and extended filaments exist along its western edge. A large amount of obscuration is evident interior to the shell. The bright nebula IC 2966 is also located within the shell at 11h50m15s, −64°51' (J2000). Brand et al. (1986) list the nebula as BBW 374 in their catalogue. From CO measurements (Brand et al. 1987; Brand et al. 1993), the distance to IC 2966 is 3.28 kpc. Inside the nebula is the star VBH 56a (van den Bergh & Herbst 1975). It is of spectral type B0.5V, $V_0 = 11.47$, $V_0 − M_V ∼ 12.7$, giving $d ∼ 3.5$ kpc. This indicates the star may be exciting IC 2966 but probably not the larger surrounding shell. If an association is real, using the distance to IC 2966 gives a size of ∼60 pc for G296.2−2.8.

A number of possible scenarios may explain the nature of this object:

1. The interaction of an SNR in the line of sight of the dark cloud and the cloud could produce a ring of filamentary emission.
2. The filamentary emission may represent a photodisassociation region produced as the cloud is exposed to ionising radiation from a nearby source.

3. The filamentary shell may be the result of an SNR associated with the dark cloud.

4. The star VBH56a may be responsible for the bright nebula IC 2966 and the larger 1° shell, though the energetics make this unlikely.

A similar, but much closer object that may be compared with G296.2$-$2.8 is the Coalsack Loop (Walker & Zealey 1998), where a 10° ring of Hα emitting nebulosity surrounds the Coalsack Nebula. This loop is estimated to be between 33 pc and 43 pc in diameter. In this case weak radio emission has been identified with the shell, but there is again no obvious exciting source of the shell.

3.3 G304.7$-$3.1

G304.7$-$3.1 is an arc of filamentary emission (Figure 3) about 1° in size. The brightest of its filaments are towards the southeast, additional faint filaments can be seen extending outside the figure to the northeast. These appear to be part of the northern edge of a larger diffuse emission feature which is clearly visible both optically and in the Parkes-MIT-NRAO (PMN) 4850 MHz survey (Griffith & Wright 1993). This diffuse optical emission directly overlies the radio emission which forms the 9° radio/Hα shell G303.5$+$0 surrounding the Coalsack (Duncan et al. 1995; Walker & Zealey 1998). The sharp filaments lie just inside this shell and may be part of the same shell.

These filaments have been associated with the WC6 type Wolf-Rayet star 9 Mus (HD 113904) (Heckathorn et al. 1982) which lies about 30' to the north. Its distance has been measured as 2.27 kpc (van der Hucht 2000). Imaging and spectroscopy (Giménez de Castro & Niemela 1998) show the filaments to be bright in Hα and [O III] while weak in [S II], and to have line ratios consistent with H II regions.

As the visible structure forms only a small part of a possible shell, an association with 9 Mus must remain uncertain.

3.4 G310.2$-$2.8

The extensive isolated emission of this object is the most unusual in our sample. A main body of faint filamentary emission is seen to extend for $\sim$1.5°, along with two small patches of emission separated from this by $\sim$20’ (Figure 4). This object is visible in the PMN radio survey, one of the small Hα filaments corresponding with bright extended radio emission at 13°55.5’$-$64°35’ (2000). The filament appears projected on the large 2.7° $\times$ 3.5° radio shell G310.5$-$3.5 (Duncan et al. 1997), and so we may be seeing optical emission from the front or back edge of the shell. In addition images taken with Mike Bessell’s wide field imaging equipment at Siding Spring Observatory (Buxton, Bessell & Watson 1998) clearly show the optical emission in Hα and [S II] (6716Å, 6731Å), indicating the presence of shock excited material. This region has been imaged with the Australia Telescope Compact Array (ATCA) (Roy Duncan 1998, private communication), showing the presence of polarised and non-thermal emission.

A radio image of the region, centred on 13°57m31s, $-$63°54’ (J2000), has also been obtained on 3 April 1997, using MOST (Figure 5) at a frequency of 843 MHz in its wide-field mode. In this mode the field size is 163’ $\times$ 163’ cosec $|\delta|$, the rms noise level is 1–2 mJy beam$^{-1}$, and the resolution (FWHM) is 43” $\times$ 43” cosec $|\delta|$. Further details of the MOST telescope and its operating modes are given in Bock, Large & Sadler (1999) and references therein. Diffuse emission is visible over about 10’ diameter at the same location as seen in the PMN radio survey, peaking at $\sim$5.7 mJy beam$^{-1}$. A faint arc of emission is visible just north of this at declination $-$64°20’. This image structure is very similar to that seen with the ATCA. The lines across
the middle and along the bottom are grating ring artifacts from bright radio sources.

The general impression is that the diffuse optical emission matches radio features at 13°55.5′, −64°35′ and possibly at 14°00′, −65°. However the crisp filamentary structure visible optically has no counterpart in the radio. Further work on this object will be needed with improved sensitivity and resolution in order to detect its full extent and to establish a link between the optical and radio emission. While it is clear that we are seeing an SNR in radio emission, a physical link with the optical emission needs to be established.

3.5 G340.5+0.7
Zealey et al. (1979) noted the presence of optical filaments west and northwest of the teardrop shaped globule Barnard 235 near the SNR G340.4+0.4. An image of this region obtained for the Hα survey shows very clearly this brighter filament, whose shape closely matches the shape of the edge of the globule, and fainter filaments to the northwest of this filament (Figures 6 and 7). Additional filaments are located to the north of the bright filament in a region of enhanced emission (Figure 8). Some very faint features below this emission region can only be seen on the film. The arc of emission close to the globule could be due to photoionisation by a nearby source or a supernova shock. The associated filamentary emission to the north, well away from the globule, makes a supernova shock more likely. It is possible that we are seeing extended emission from the western edge of a shell structure ~20° in size. Unfortunately no related emission is visible in available radio surveys or IRAS data.

3.6 Kes 45
Kes 45 (G342.1+0.1, MSH 16-48, MHR 58) is a 30′ diameter radio source located at 16°23′36″, −43°35′ (J2000).
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Figure 9  Diagram showing major filamentary structures in the Kes 45 region.

It has been considered an SNR based on its spectral index $\alpha = -0.50$ at 1 GHz (Milne 1970), although subsequently it has been lost from SNR catalogues. Improved resolution radio observations (Caswell & Clark 1975) resolved several sources in this region. Two of these, G341.9−0.3 and G342.0−0.2, are now known to be SNRs. However, as noted, the low frequency flux density of these sources is much less than the MSH flux density (Mills, Slee & Hill 1960), so an extended object is likely to be present.

Optically, images of the region show a network of filaments over an area 30′ in diameter (van den Bergh et al. 1973; Zealey et al. 1979) interacting with elephant trunk structures (Frieman 1954), instabilities that can form in expanding shock and ionisation fronts. Spectra in the visible region (Danziger & Dennefeld 1974; Danziger & Dennefeld 1976) indicate enhanced [S ii] emission relative to Hα and weak [O iii] 5007 Å emission, but the underlying H ii region makes any interpretation very difficult.

Hα survey images show filamentary emission covering an area 1.5° in diameter. The main features are indicated in Figure 9. In Figure 10 a closeup is shown of the western group of filaments identified by van den Bergh et al. (1973). These filaments indicate an association with a dark cloud in the shell of NGC 6231. New features include two filaments to the east located near 17h00m, −44°00′ (J2000), and a large number of filaments to the northeast, a section of which is shown in Figure 11.

If these optical filaments represent a single object, then the diameter, assuming an association with the NGC 6231 H ii region to the north (Zealey et al. 1979), becomes 36 pc.

The combination of size, extensive optical emission and low radio flux indicate that Kes 45 is in an advanced state of evolution.

4 Conclusions

Using films from the AAO/UKST Hα Survey we have identified four large filamentary shell structures, one of these a new possible Wolf–Rayet shell, and new optical emission in two known SNR candidates. These objects are:

- G245.9+0.9, a faint 1°20′ optical shell surrounding the Wolf–Rayet star HD 65865

Figure 10  Closeup of central western section of Kes 45.

Figure 11  Closeup of northeast quadrant of Kes 45.
G296.2−2.8, a 1° optical shell with interior absorption, possibly associated with the star V838 Sct.
G304.7−3.1, an arc of filamentary emission on the edge of a larger shell structure, and likely associated with θ Mus.
G310.2−2.8, a filamentary structure with an unusual morphology and associated radio emission.
G340.5±0.7, a small patch of optical filaments.
Kes 45, a system of optical filaments 1.5° in diameter, which has long been suspected as an SNR.
Techpan film used with the new Hα filter is detecting fainter and more distant filamentary structures in comparison with previous photographic surveys, due to the improved spatial resolution, red sensitivity of the film, and narrow bandpass of the filter.

Based on the discovery rate and survey completion, we expect that 16 or more large filamentary structures may be discovered by this survey.

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