Mem. S.A.It. Vol. 76, 534
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Some statistics of Galactic SNRs

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Abstract. The selection effects applicable to the identification of Galactic supernova remnants (SNRs) at radio wavelengths are discussed. Low surface brightness remnants are missing, as are those with small angular sizes (including young but distant SNRs). Several statistical properties of Galactic SNRs are discussed, including the surface-brightness/diameter ($\Sigma{-}D$) relation. The wide range of intrinsic properties of Galactic remnants with known distances, and the observational selection effects, means that the $\Sigma{-}D$ relation is of limited use to derive diameters and hence distances for individual SNRs, or for statistical studies.

Key words. supernova remnants – radio continuum: ISM – ISM: general

1. Introduction

Over two hundred Supernova Remnants (SNRs) have been identified in our Galaxy. I have produced several versions of a catalogue of Galactic SNRs over the last twenty years, the most recent revised in 2004 January (Green 2004). Here I review some of the statistical properties of Galactic remnants based on the most recent version of the catalogue. In particular I emphasize the importance that the selection effects applicable to the identification of Galactic SNRs must be appreciated.

2. The catalogue

The catalogue of Galactic SNRs exists in two formats. First – published as an appendix to Green (2004) – the basic parameters (Galactic and equatorial coordinates, size, type, radio flux density, spectral index, and other names) for each remnant. Second, a more detailed version, available on the World-Wide-Web[1] which includes the descriptions of each remnant, additional notes and references. The detailed version of the catalogue is available as postscript or pdf for downloading and printing, or as web pages. The web pages include links to the 'NASA Astrophysics Data System' for each of the nearly one thousand references. Notes both on those objects no longer thought to be SNRs, and on the many possible and probable remnants that have been reported, are also included in the detailed version of the catalogue. It should be noted that the catalogue is far from homogeneous. It is particularly difficult to be uniform in terms of which objects are considered as definite remnants, and are included in the catalogue, rather than listed as possible or probable remnants which require further observations to clarify their nature. Since the first version of the catalogue was published in Green (1984) the number of identified Galactic SNRs has increased considerably, from 145 to

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[1] See `http://www.mrao.cam.ac.uk/surveys/snrs/`.

231. Much of this increase has been due to the availability of large area radio surveys, particularly the Effelsberg survey at 2.7 GHz, and the MOST survey at 843 MHz, which are discussed further below (Section 3.1).

3. Selection effects

In practice the dominant selection effects applicable to identification of Galactic SNRs are those that are applicable at radio wavelengths. Simplistically, two selection effects apply (e.g. Green 1991), due to the difficulty in identifying (i) faint remnants and (ii) small angular size remnants.

3.1. Surface brightness

SNRs need to have a high enough surface brightness for them to be distinguished from the background Galactic emission. This selection effect is *not* uniform across the sky, both because the Galactic background varies with position, and because the sensitivities of available wide area surveys covering different portions of the Galactic plane vary. The most recent large-scale radio surveys that have covered much of the Galactic plane are: (i) the Effelsberg survey at 2.7 GHz (Reich et al. 1990; Fürst et al. 1990), which covered $358^\circ < l < 240^\circ$ and $|b| < 5^\circ$; and (ii) the MOST survey at 843 MHz (Whiteoak & A. J. Green 1996; A. J. Green et al. 1999)[2], which covered $245^\circ < l < 355^\circ$, but only to $|b| < 1\overset{\circ}{.}5$. In the current catalogue of SNRs, fainter remnants are relatively more common in the anti-centre and away from $b = 0^\circ$, where the Galactic background is lower (see Green 2004).

Since the new SNRs identified from the Effelsberg survey were included in the version of the SNR catalogue published in Green (1991), the surface brightnesses of remnants in the survey region that have subsequently been identified are useful for estimating the completeness limit for this survey. Since 1991 an additional 24 remnants within $358^\circ < l < 240^\circ$ and $|b| < 5^\circ$ have been included in the catalogue, most in the first quadrant. The surface brightnesses of these remnants suggest a completeness limit of $\Sigma \approx 10^{-20}$ W m^{-2} Hz^{-1} sr^{-1}, at 1 GHz, for the Effelsberg survey (see Green 2004,for further discussion). And since the number of remnants brighter than this value is similar in the 1st and 4th quadrants, then a similar limit seems appropriate for the MOST survey region.

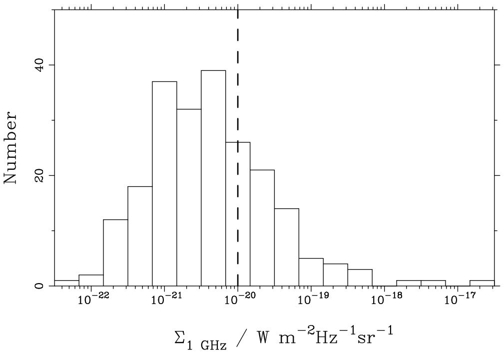

Fig. 1. Distribution in surface brightness at 1 GHz of 217 Galactic SNRs. The dashed line indicates the surface brightness completeness limit discussed in Section 3.1.

Thus, the surface brightness limit for completeness of the current catalogue of Galactic SNRs is approximately 10^{-20} W m^{-2} Hz^{-1} sr^{-1}. Fig. 1 shows a histogram of the surface brightnesses of the 217 Galactic SNRs, of which 64 are above this nominal surface brightness limit.[3] The SNRs with surface brightnesses below this limit are predominantly in regions of the Galaxy where the background is low, i.e. in the 2nd and 3rd quadrants, and away from $b = 0^\circ$, as shown in Fig. 2.

Ongoing and future observations will no doubt continue to detect more Galactic SNRs, although it seems very likely that most of these objects will be faint, and hence difficult to study in detail. Currently there are several large scale radio surveys underway that will cover much of the Galactic plane [4]. As is discussed in

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[2] To avoid confusion between authors with the same surname, I include initials for Anne J. Green, of the University of Sydney, Australia.

[3] For 14 catalogued remnants no reliable radio flux density, or only a limit is available.

[4] See: `http://www.ras.ucalgary.ca/IGPS/` for further information.

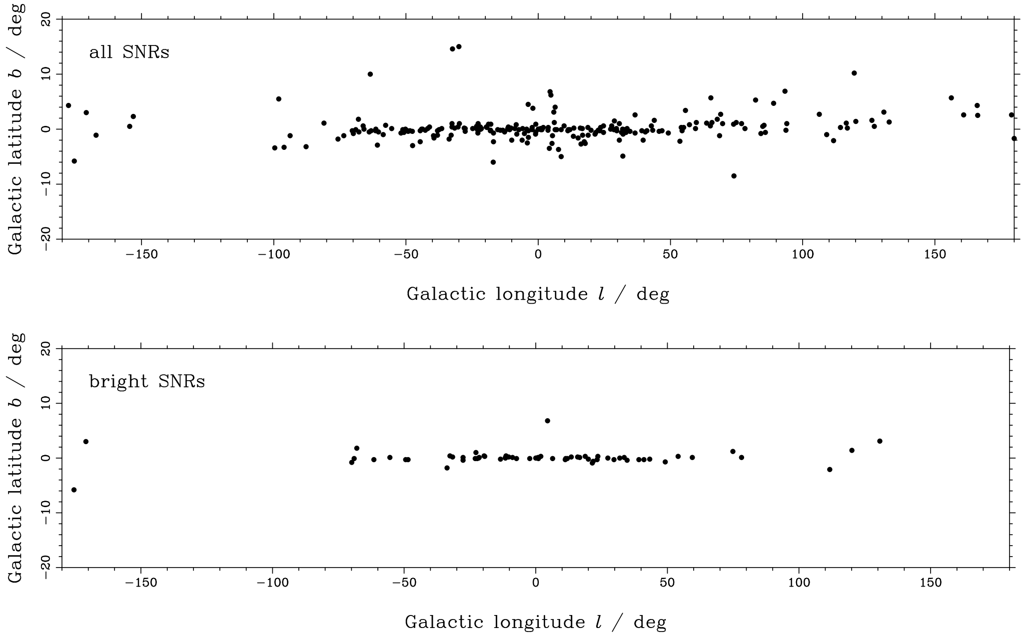

Fig. 2. Galactic distribution of (top) all Galactic SNR and (bottom) those SNRs with a surface brightness at 1 GHz greater than 10^{-20} W m^{-2} Hz^{-1} sr^{-1}. (Note that the latitude and longitude axes are not to scale.)

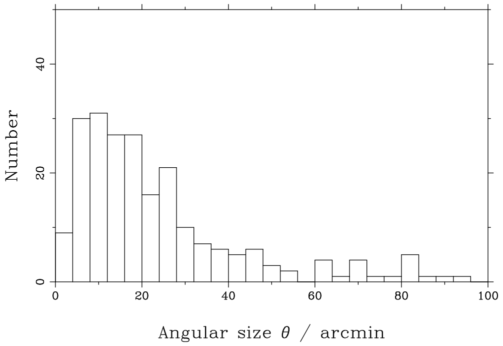

Fig. 3. Histogram of the angular size of 219 Galactic SNRs (12 remnants larger than 100 arcmin are not included).

Section 5.2, there is a general trend that fainter remnants tend to be larger, and hence on average older, than brighter remnants. However, because of the wide range of properties of Galactic SNRs with known distances, the surface brightness selection effect applies not just to old remnants, but also to young remnants.

3.2. Angular size

Current catalogues are also likely to be missing small angular size SNRs, as their structure is not well resolved by the available Galactic plane surveys, and they would not be recognised as likely SNRs. Fig. 3 is shows the histogram of the angular sizes of known remnants, which peaks at around 10 arcmin. The limiting angular size varies for the different available wide area surveys. As discussed above, the radio survey that covers most of the Galactic plane is the Effelsberg 2.7-GHz survey, which has a resolution of ≈ 4.3 arcmin. So, for this survey, any remnants less than about 13 arcmin in diameter (i.e. 3 beamwidths) are not likely to be recognised from their structures (although, as discussed below in Section 3.3, some searches have been made for small remnants among compact sources in the Effelsberg 2.7-GHz survey). The MOST 843-MHz survey has a much better resolution, ≈ 0.7 arcmin, which implies that in the region of the Galactic plane covered by this survey only remnants smaller than about ≈ 2 arcmin (i.e. 3

beamwidths) might be expected to be missed. However, although the MOST survey detected 18 new SNRs (Whiteoak & A. J. Green 1996), the smallest new remnant was G345·7−0·2, which is 7 × 5 arcmin^2 in extent, i.e. several times larger than the nominal limit of ≈ 2 arcmin. Thus it is difficult to quote a single angular size selection limit for current SNR catalogues, although it is clear that it is difficult to identify small angular size remnants from existing wide area surveys.

3.3. Missing young but distant SNRs

The lack of small angular size remnants is particularly clear when the remnants of known 'historical' Galactic supernovae (see Stephenson & Green 2002) are considered. These remnants are relatively close-by – as is expected, since their parent SNe were seen historically – and therefore sample only a small fraction of the Galactic disc. Consequently many more similar, but more distant remnants are expected in our Galaxy (e.g. Green 1985), but these are not present in the current catalogue.

Table 1 gives the distances, angular sizes, flux densities and surface brightnesses at 1 GHz, for the remnants of known historical supernovae from the last thousand years, plus Cas A (which although its supernova was not seen – so it is not strictly a historical remnant – is known to be only about 300 years old). This table also lists the parameters of these remnants when scaled to larger distances of 8.5 and 17 kpc, i.e. to represent how they would appear if they if they were at the other side of the Galaxy.

From Table 1, any young SNRs in the Galaxy similar to the known historical remnants, but in the far half of the Galaxy, would generally be expected to have angular sizes less than a few arcmin, usually with high surface brightness, greater than ≈ 10^{-19} W $\text{m}^{-2}\,\text{Hz}^{-1}\,\text{sr}^{-1}$ (although remnants similar to the remnant of the SN of AD 1006 would be much fainter). These remnants would also be expected to lie close to the Galactic plane, with $|b| \lesssim 1^\circ$. Several dozen other young (i.e. less than a thousand year old) SNRs are expected in the Galaxy (see Green 2004,for further discussion). However, there are very few such remnants in the current Galactic SNR catalogue. In fact there are only 3 known remnants with angular sizes of 2 arcmin or less: G1·9+0·3, G54·1+0·3 and G337·0−0·1. (It should be noted that there are unlikely to be other luminous remnants in the Galaxy like Cas A and the Crab nebula. Any such remnants, even on the far side of the Galaxy, would have relatively high flux densities, and the nature of all such sources in the Galactic plane is known.)

Since the missing young but distant remnants are expected to have angular sizes of a few arcmin or less, they will not have been resolved sufficiently in large area radio surveys. Higher resolution, targeted observations are needed to identify any such small remnants, and although there have been several such searches for remnants of this type (e.g. Green & Gull 1984; Helfand et al. 1985; Green 1985, 1989; Sramek et al. 1992; Misanovic et al. 2002, see also Saikia et al. 2004), they have had only limited success (identifying the small remnants G1·9+0·3 and G54·1+0·3 noted above). (An additional candidate small, presumably young SNR is G337·2+0·1, which was listed as a possible SNR by Whiteoak & A. J. Green. Recently Combi et al. (2005) – see also these proceedings – have also noted that this source is associated with an X-ray source listed by Sugizaki et al. (2001), which supports the SNR identification.[5])

The fact that such missing, small remnants are likely to be in complex regions of the plane may mean that confusion is a very significant problem, and not just at radio wavelengths. Further searches for these missing young but distant remnants are clearly required.

4. Some simple SNR statistics

In the current version of the catalogue, 77% of remnants are classed as shell type (or possible shell), 12% are composite (or possible

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[5] Note that the radio surface brightness for G337·2+0·1 given by Combi et al. (2005) is too low by two orders of magnitude.

Table 1. Parameters of known historical SNRs, plus Cas A.

			as observed			if at 8.5 kpc		if at 17 kpc	
date	name or remnant	distance /kpc	size /arcmin	$\Sigma_{1\ \mathrm{GHz}}$ /W m^{-2} Hz^{-1} sr^{-1}	$S_{1\ \mathrm{GHz}}$ /Jy	size /arcmin	$S_{1\ \mathrm{GHz}}$ /Jy	size /arcmin	$S_{1\ \mathrm{GHz}}$ /Jy
–	Cas A	3.4	5	1.6×10^{-17}	2720	2.0	435	1.0	109
AD 1604	Kepler's	2.9	3	3.2×10^{-19}	19	1.0	2.2	0.5	0.55
AD 1572	Tycho's	2.3	8	1.3×10^{-19}	56	2.3	4.1	1.1	1.0
AD 1181	3C58	3.2	7	1.0×10^{-19}	33	2.6	4.7	1.3	1.2
AD 1054	Crab nebula	1.9	6	4.4×10^{-18}	1040	1.4	52	0.7	13
AD 1006	G327·6+14·6	2.2	30	3.2×10^{-21}	19	7.7	1.3	3.9	0.31

composite), and 4% are filled-centre (or possible filled centre) remnants. The remaining 7% have not yet been observed well enough to be sure of their type, or else are objects which are conventionally regarded as SNRs although they do not fit well into any of the conventional types (e.g. CTB80 (=G69·0+2·7), MSH 17−39 (=G357·7−0·1)).

There are 14 Galactic SNRs that are either not detected at radio wavelengths, or are poorly defined by current radio observations, so that their flux density at 1 GHz cannot be determined with any confidence: i.e. 94% have a flux density at 1 GHz included in the catalogue. Of the catalogued remnants, 36% are detected in X-ray, and 23% in the optical. At both these wavelengths, Galactic absorption hampers the detection of distant remnants.

5. Distance dependent SNR statistics

5.1. Distances to SNRs

Accurate distances are not available for most known SNRs, which is a problem for many studies of Galactic SNRs, where it is necessary to know the distances to remnants (or equivalently their physical sizes, since their angular sizes are known). The distances that are available are obtained from a wide variety of methods, each of which is subject to their own uncertainties, and some of which are subjective. In the next few years further distance measurements should become available for more SNRs, both because of the various ongoing Galactic plane survey, and new distance measurement techniques: e.g. from H I column densities (see Foster & Routledge 2003), or H I absorption to polarised emission from remnants (Kothes et al. 2004). Currently (see Green 2004), the distances to 47 Galactic SNRs are available, i.e. only 20% of known Galactic SNRs. The uncertainties in these distances are far from uniform. For kinematic distances – which are a large majority of the available distances – there are always some uncertainties in deriving distances from observed velocities, due to deviations from circular motion (especially an issue for nearby remnants, and for those near $l = 0°$ and $180°$ where the observed velocity does not depend strongly on distance) and ambiguities inside the Solar Circle.

5.2. The Σ–D and L–D Relations

Many statistical studies of Galactic SNRs have relied on the surface-brightness/diameter, or 'Σ–D' relation to derive distances for individual SNRs from their observed flux densities and angular sizes. For remnants with known distances (d), and hence known diameters (D), physically large SNRs are fainter (i.e. they have a lower surface brightness) than small remnants. Using this correlation between Σ and D for remnants with known distances, a physical diameter is deduced from the distance-independent *observed* surface brightness of any remnant. Then a distance to the remnant can be deduced from this diameter and the observed angular size of the remnant.

The Σ–D relation for Galactic SNRs with known distances is shown in Fig. 4. This

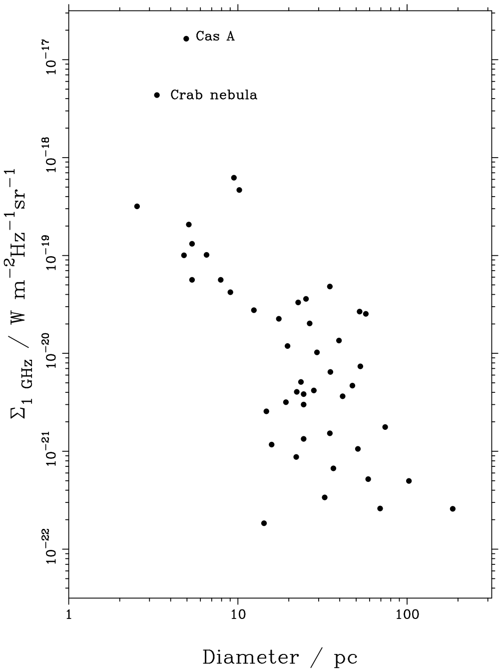

Fig. 4. The surface brightness/diameter (Σ–D) relation for 47 Galactic SNRs with known distances. Note that the lower left part of this diagram is likely to be seriously affected by selection effects.

clearly shows a wide range of diameters for a given surface brightness, which is a severe limitation in the usefulness of the Σ–D relation for deriving the diameters, and hence distances, to individual remnants. For a particular surface brightness, the diameters of SNRs vary by up to about an order of magnitude, or conversely, for a particular diameter, the range of observed surface brightnesses seen varies by more than two orders of magnitude.

The correlation shown between surface brightness and diameter in Fig. 4 is, however, largely a consequence of the fact that it is a plot of surface-brightness – rather than luminosity – against diameter, D. Surface brightness is plotted, because it is the distance-independent observable that is available for (almost) all SNRs, including those for which distances are not available. For remnants whose distances are known, we can instead consider the radio luminosity of the remnants. Since Σ and luminosity,

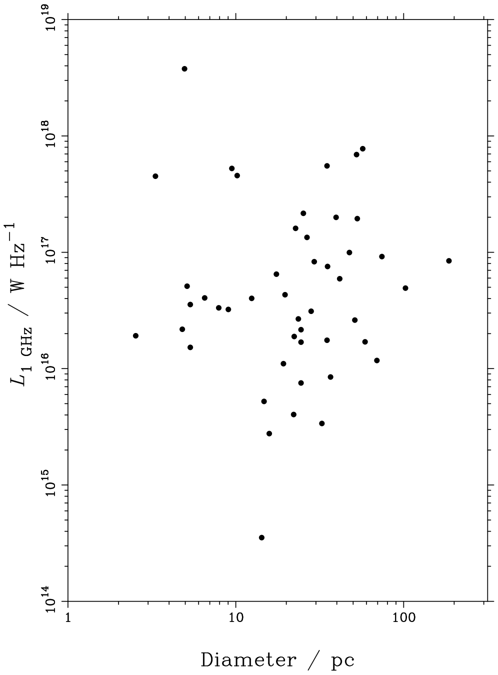

Fig. 5. The luminosity/diameter (L–D) relation for 47 Galactic SNRs with known distances.

L, depends on the flux density S, angular size θ, distance d and diameter D, as

$$\Sigma \propto \frac{S}{\theta^2} \quad \text{and} \quad L \propto S d^2$$

then

$$\Sigma \propto \frac{L}{(\theta d)^2} \quad \text{or} \quad \Sigma \propto \frac{L}{D^2}.$$

Thus, much of the correlation shown in the Σ–D relation in Fig. 4 is due to the D^{-2} bias that is inherent when plotting Σ against D, instead of L against D. The L–D relation for Galactic SNRs with known distances in Fig. 5 shows that there is wide range of luminosities for SNRs of all diameters. Cas A is the most luminous Galactic SNR, but it appears to be at the edge of a wide distribution of luminosities. The wide range of luminosities is perhaps not surprising, given that the remnants are produced for a variety of types of supernovae, and that they evolve in regions of ISM with a range of properties (e.g. density), which may well effect the efficiency of the radio emission mechanism at work. For example, some SNRs may initially evolve inside a low-density, wind-blown cavity, and then collide with the much denser regions of the surrounding ISM.

Furthermore, the full range of intrinsic properties of SNRs may be even wider than that shown in Figs 4 and 5, as the selection effects discussed in Section 3 mean that it is difficult to identify small and/or faint SNRs.

Also, it is not clear that any best-fit Σ–D relation – not withstanding selection effect problems – actually represents the evolutionary track of individual SNRs (see, for example, Berkhuijsen 1986, or Berezhko & Völk 2004 for a recent discussion). The distribution of SNRs with known distances is a snapshot in time of a population of remnants, and individual remnants may evolve in the Σ–D plane in directions quite different from any power law fitted to the overall distribution of SNRs (or to the upper limit of the distribution). As a simple example, consider the situation where SNRs have a range of intrinsic luminosities, expand with a constant luminosity up to some particular diameter – which varies for different SNRs depending on their environment (e.g. the surrounding ISM density, which influences their expansion speed, which may affect the efficiency of radio emission mechanism) – after which their radio luminosity fades rapidly. In this case, the locus of the upper bound to the highest surface brightness remnants for a particular diameter is related to where the luminosities of different SNRs begin to decrease, and does not represent the evolutionary track of any individual remnant.

5.3. A question of regression

There is a further issue related to any power law $\Sigma \propto D^n$ fits to the observed properties of samples of SNRs, even if any problems with the selection effects are neglected. The Σ–D relation has two particular uses, first, the derivation of diameters (and hence distances) for Galactic remnants from their observed surface brightnesses, and second, to parameterise the relationship between surface brightness and diameter, for comparison with models and theories, or between different samples of SNRs. For the former, the measured value of Σ is used to predict D, and in this case a least squares fit minimizing the deviations in $\log D$ should be used (see Isobe et al. 1990 for a discussion of least squares fitting). This, however, has not always been done, and instead fits minimizing the deviations in $\log \Sigma$ have been used. The differences between these two least square fits can be very large for remnants much fainter or brighter than the average surface of the remnants with known distances used to calibrate the Σ–D relation. For example, Case & Bhattacharya (1998) derived a best fit Σ–D relation with a slope (n above) of -2.38 ± 0.26 using a sample of 36 shell SNRs (excluding Cas A) evidently by minimizing the square of the deviations in $\log \Sigma$. Instead minimizing the deviations in $\log D$ – which is appropriate if the relation is to be used to *predict* diameters from surface brightnesses – leads to a much steeper fit, with a power law slope of -3.37 ± 0.35. This means that Case & Bhattacharya's "best fit" overestimates the diameters, and hence also the distances of fainter remnants. To quantify this, a faint remnant with a surface brightness of 3×10^{-22} W m^{-2} Hz^{-1} sr^{-1} at 1 GHz, would have its diameter overestimated by about 40%, which is larger than the nominal uncertainty that Case & Bhattacharya claimed (although there is evidently a wide spread of intrinsic properties of SNRs with known distance, see Fig. 4). If a $\Sigma \propto D^n$ relation is to be used to describe the relationship between Σ and D, then arguably (see Isobe et al.) a fit to observations that treats Σ and D symmetrically is appropriate (e.g. the bisector of least square fits made minimizing either $\log \Sigma$ or $\log D$).

6. Galactic SNR distribution

The distribution of SNRs in the Galaxy is of interest for many astrophysical studies, particularly in relation to their energy input into the ISM and for comparison with the distributions of possible progenitor populations. Such studies are, however, not straightforward, due to observational selection effects and the lack of reliable distance estimates available for most identified remnants. In particular, all SNRs in the anti-centre (i.e. 2nd and 3rd Galactic quadrants) are outside the Solar Circle, at large Galactocentric radii. These are regions where the background Galactic emission is faint, so that low surface brightness remnants are relatively easy to identify (see Section 3). Without taking selection effects into account, the larger number of fainter SNRs in the anti-centre leads to an apparently broad distribution of Galactic SNRs in Galactocentric radius (e.g. see further discussion in Green 2004). A simple approach is to compare the distribution in Galactic longitude of bright remnants, with $\Sigma_{1\ \mathrm{GHz}} > 10^{-20}$ W m^{-2} Hz^{-1} sr^{-1} where selection effects are not important, with the expected distribution for various models. In Green (2004) this was done with 64 bright remnants, and simple Monte Carlo models of a Gaussian distribution, where the probability distribution varies with Galactocentric radius, R, as $\propto \mathrm{e}^{-(R/\sigma)^2}$, where σ is the Galactocentric scale length. A simple least squares comparison[6] of the observed and model cumulative distributions indicates that for this simple model a scale length of $\sigma \approx 6.5$ kpc best matches the observed distribution of high brightness SNRs.

7. Conclusions

In statistical studies of Galactic SNRs it is crucial that the selection effects that apply to the identification of remnants are taken into account. Both faint (i.e. low surface brightness) and small angular size remnants are missing from current catalogues of Galactic SNRs. A consequence of the angular size selection effect is that few young but distant remnants have yet been identified in the Galaxy. For remnants with known distances, the intrinsic range of luminosity of Galactic SNRs is large, which combined with selection effects, means that the $\Sigma{-}D$ relation is of limited use for determining distances to individual remnants, or for statistical studies.

Acknowledgements. I am grateful to many colleagues for numerous comments on, and corrections to, the various versions of the Galactic SNR catalogue. This research has made use of NASA's Astrophysics Data System Bibliographic Services.

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[6] Not a χ^2 comparison, as erroneously stated in Green (2004).