Theoretical Derivation of $\Sigma$-$D$ Relation of Galactic SNRs

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ABSTRACT

We derive the $\Sigma$-$D$ relation of Galactic supernova remnants of shell-type separately at adiabatic-phase and at radiative-phase through two sets of different formulas, considering the different physical processes of shell-type remnants at both stages. Also statistics on Galactic shell-type remnants about 57 was made. Then we do some comparison with other results obtained before. It shows that all the best fit lines in the $\Sigma$-$D$ relation plots newly are to some extent flatter than those derived by some authors at early time. Our theoretical and statistical outcomes are in somewhat good consistency.

Subject headings: methods: — statistical — analysis — (ISM:) supernova remnants

1. Introduction

The relation between the radio surface brightness ($\Sigma$) and the diameter ($D$) of SNRs has being widely discussed before (e.g., Poveda & Woltjer 1968; Clark & Caswell 1976; Green 1984; Mills et al. 1984; Huang & Thaddeus 1985; Arbutina et al. 2004, etc.). Many authors use them to determine the distance of a SNR (Poveda & Woltjer 1968; Clark & Caswell 1976; Lozinskaya 1981; Huang & Thaddeus 1985; Duric & Seaquist 1986; Guseinov et al. 2003). There are some different outcomes about the best fit line of the $\Sigma$-$D$ relation. Despite that one straight line was derived by some workers in their statistics (e.g., Poveda & Woltjer 1968; Clark & Caswell 1976), there are some broken lines in their previous derivation. At 408 MHz Clark & Caswell (1976) have a broken line with slopes of $\beta = -2.7/ -10$ ($\Sigma \propto D^\beta$) at $D \leq 32$ pc/$D \geq 32$ pc. While at 1 GHz Allakhverdiyev et al. (1985) gave line slope of $-3.0$ and $-6.0$ with broken point at $D = 40$ pc. Theoretical analysis once made by Duric & Seaquist (1986) got following results

\[
\Sigma(D) = 4 \times 10^{-15} D^{-3.5}, D \ll 1pc \quad (1)
\]
\[
\Sigma(D) = 4 \times 10^{-14} D^{-5}, D \gg 1pc \quad (2)
\]

With the line broken at 1 pc when the remnants are far too small to be detected.

Galactic SNRs are classified into three types: Shell-type, Plerion-type and Composite-type. Merely shell-type remnants are analyzed in our work. Furthermore, shell-type SNRs usually have four evolution stages: the free expansion phase, the Sedov or adiabatic phase, the radiative or snowplough phase and the dissipation phase. Nearly all of the detected SNRs are in the adiabatic-phase, or in the 3rd. Almost none is observed in the 1st and 4th phases. Here we do a simple statistics on the $\Sigma$-$D$ relations of some Galactic SNRs in section$^2$ and do some theoretical reductions of $\Sigma$-$D$ relations independently at adiabatic-phase and radiative-phase in section$^3$ and some comments made in section$^4$. In the last section summarizes our conclusion.

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2. Statistics of $\Sigma$-D relation

We newly collected 57 shell-type remnants (table 5) in Galaxy with known distance ($d$) which are derived not by $\Sigma$-D relation but by some other different methods to make statistics, and get relation as follow,

$$\Sigma(D) = 5.50 \times 10^{-18} D_{pc}^{-2.15 \pm 0.38} \left( W m^{-2} Hz^{-1} sr^{-1} \right)$$

(3)

The SNR G4.5+6.8 (Kepler) in table 5 was excluded since its extremely small linear diameter (3 pc only) so as to avoid large deviation of fitting. Another source SNR G166.2+2.5 was also not used for being a false remnant. In Fig. 1 the $\Sigma$-D relation was shown. It seems that the best fit lines in plot are somewhat flatter than those derived by some authors at early time (e.g., Clark & Caswell 1976, 1979; Milne 1979; Allakhverdiyev et al. 1985; Duric & Seaquist 1986). In the following we do some theoretical works about the $\Sigma$-D relation of the remnants.

3. Theoretical reduction

The physical processes of supernova remnants at Sedov-phase are rather different with that at radiative-phase. Therefore we do theoretical derivation of the $\Sigma$-D relation of remnants separately for both stages, since SNR at both free-expansion phase and last phase are practically undetectable.

3.1. $\Sigma$-D relation at Sedov-phase

Assuming the remnants linear diameter ($D$) in pc, SNe initial explosion energy ($E_{51}$) in the unit of $10^{51}$ ergs, and ISM electron density ($n_0$) in $cm^{-3}$, from the standard Sedov solution we have the following well-known equation for remnants at second stage (Itoh 1978, Bignami & Caraveo 1988, Zaninetti 2000, Völk et al. 2002, Ptuskin & Zirakashvili 2003)

$$D(t) = 4.3 \times 10^{-11} \left( \frac{E_{51}}{n_0} \right)^{1/5} t^{2/5}$$

(4)

After making differentiation $\frac{dD(t)}{dt}$ (Duric & Seaquist 1986), one has

$$v(t) = \frac{2}{5} A_0 t^{-3/5}$$

(5)

where

$$A_0 = 4.3 \times 10^{-11} \left( \frac{E_{51}}{n_0} \right)^{1/5}$$

(6)

At adiabatic phase the remnants thicknesses are proportional to $D$ (Milne 1970). Then we have the shell volume as

$$V(D) = C_0 D^3$$

(7)

Here

$$C_0 = \frac{\pi}{6} \left( 1 - \left( \frac{D_i}{D_o} \right)^3 \right) \simeq 0.37$$

(8)

when we approximately assume $D_i/D_o \sim 2/3$. $D_i(D_o)$ is the inner(outer) diameter of the remnant shell. Combining (3) and (6), one gets

$$V(t) = C_0 A_0^3 t^{6/5}$$

(9)

As the remnants shock waves travel at the Sedov-phase, the ambient magnetic field $B$ will decrease with $D$ according to (Padmanabhan 2000)

$$B(D) = B_0 \left( \frac{D_o}{D} \right)^2$$

(10)

Substituting (3) to it, we have

$$B(t) = B_0 D_o^2 A_0^2 t^{-4/5}$$

(11)
While Duric (2000) shows that at the adiabatic phase of remnants evolution, their radio emissivity $\epsilon(B, v)$ is expressed as

$$\epsilon(B, v) = 3 \times 10^{-34} n_0 \left( \frac{B}{10^{-2}\text{G}} \right)^{\alpha+1} \times \left( \frac{\nu}{7000\text{KHz}} \right)^{-2\alpha} \left( \frac{\nu}{G\text{Hz}} \right)^{-\alpha} \left( WH\text{z}^{-1}\text{m}^{-3} \right)$$

Where, the magnetic field $B$ is expressed in units of $10^{-4}$ G, the velocity of shock wave in units of 7000 km s$^{-1}$, and radiation frequency in GHz. by (4), (10) and taking the average value of the remnants spectral index $\alpha = 0.5$, we can get

$$\epsilon(t) = 0.1714 \times 10^{-40} n_0 D_0 \left( \frac{B_0}{10^{-4}\text{G}} \right)^{1/2} t^{-1}$$

when the shell volume is taken to be the radiating electrons encompassing volume, the remnants surface brightness can be given by

$$\Sigma(t) = \frac{\epsilon(t) V(t)}{\pi^2 D^2(t)} = 0.1714 \times 10^{-40} n_0 D_0 \times \left( \frac{B_0}{10^{-4}\text{G}} \right) C_0 A_0 t^{-3/5}$$

combining (3) and above formula, one gets the final form

$$\Sigma(D) = m_\alpha D^{-1.5} \left( Wm^{-2}Hz^{-1}sr^{-1} \right)$$

where

$$m_\alpha = 0.1714 \times 10^{-40} n_0 D_0 \left( \frac{B_0}{10^{-4}\text{G}} \right) \frac{C_0 A_0^{-0.5}}{7.56 \times 10^{-19}}$$

Here the typical value of some SNRs physical parameters is taken: ISM density $n_0 = 0.1$ cm$^{-3}$, SNe initial explosion energy $E_{51}$, the remnants diameter and ISM magnetic field at the beginning of Sedov phase $D_0 = 2$ pc and $B_0 = 10^{-4}$ G, etc. The derived line in $\Sigma$-$D$ relation plot of the SNRs in second phase is somewhat flat

$$\Sigma(D) = 7.56 \times 10^{-19} D_0^{-1.5} \left( Wm^{-2}Hz^{-1}sr^{-1} \right)$$

### 3.2. $\Sigma$-$D$ relation at radiative-phase

Similarly assuming the remnants linear diameter ($D$) in pc, SNe initial explosion energy ($E_{51}$) in the unit of $10^{51}$ ergs, and ISM electron density ($n_0$) in cm$^{-3}$, we have the following equations for remnants at third stage (Itoh 1978)

$$D(t) = 1.42 \left( \frac{E_{51}}{n_0} \right)^{5/21} t^{2/7}$$

Which is rather deferent from formula (3). After making differentiation $\frac{dD(t)}{dt}$, we have

$$v(t) = \frac{2}{7} A_0 t^{-5/7}$$

where

$$A_0 = 1.42 \left( \frac{E_{51}}{n_0} \right)^{5/21}$$

the same as that in Sedov phase

$$V(D) = C_0 D^3$$

when we approximately take $D_i/D_o \sim 3/4$, then

$$C_0 = \frac{\pi}{6} \left( 1 - \left( \frac{D_i}{D_o} \right)^3 \right) \simeq 0.3$$

Here, $D_i(D_o)$ is defined as before. Changing the variant $D$ to $t$, one have the form

$$V(t) = C_0 A_0 t^{6/7}$$

Because that as the remnants shock waves travel at Sedov-phase the ambient magnetic field $B$ of a remnant decreases with the diameter $D$ according to (10) and at dissipation-phase according to $B(D) = B_0(D_0/D)^3$, one can moderately suppose that at radiative-phase the magnetic field $B$ will decrease with $D$ as follow

$$B(D) = \frac{D_0}{D} B_0$$

which obviously is not the same as the formula (9). After substituting (7) to it, one has

$$B(t) = \left( \frac{B_0 D_0^2}{A_0} \right) t^{-2/7}$$

At the radiative phase of remnants evolution we could assume $B_0 \sim 10^{-6}$ Gauss, and $v_0 \sim 220$ Km s$^{-1}$ for the formula in Duric (2000)

$$\epsilon(t) = 3 \times 10^{-34} n_0 D_0 \left( \frac{B}{10^{-2}\text{G}} \right)^{\alpha+1} D_0^{\alpha+1} \times A_0^{-\alpha-1} t^{-\frac{\alpha}{2}+1+1} \times \left( \frac{\nu}{GHz} \right)^{-\alpha}$$

(26)
Where, the magnetic field \( B \) is expressed in units of \( 10^{-6} \) G, the velocity of shock wave in units of 220 km \( s^{-1} \), and radiation frequency in GHz. Therefore the remnants surface brightness is expressed as

\[
\Sigma(t) = \frac{\epsilon(t)V(t)}{\pi^2 D^2(t)}
\]

\[
= 3 \times 10^{-34} \left( \frac{7}{2} \right)^{2\alpha} \frac{n_0}{\pi^2} \left( \frac{B_0}{10^{-6} G} \right) D_0^{\alpha+1}
\times A_0^{-3\alpha} C_0 \left( \frac{\nu_0}{220 K m s^{-1}} \right)^{\alpha}
\times \left( \frac{n_0}{G H_2} \right)^{\alpha} t^{-8\alpha/7}
\]  

(27)

changing the variant \( t \) to \( D \), we have the form

\[
\Sigma(D) = m_r D^{-2.0} \left( W m^{-2} H z^{-1} s r^{-1} \right)
\]  

(28)

where

\[
m_r = 3 \times 10^{-34} \left( \frac{7}{2} \right)^{2\alpha} \frac{n_0}{\pi^2} \left( \frac{B_0}{10^{-6} G} \right) D_0^{\alpha+1}
\times C_0 A_0^{-6\alpha} = 4.63 \times 10^{-18}
\]  

(29)

Here we have used the typical values for the physical initial parameters as that in section 3.2.

Thus a little steeper line of \( \Sigma-D \) relation of SNRs at 3rd phase is obtained.

\[
\Sigma(D) = 4.63 \times 10^{-18} D^{-2.0}_{pc} \left( W m^{-2} H z^{-1} s r^{-1} \right)
\]  

(30)

3.3. Transition from Sedov-phase to radiative-phase

Assuming \( D_t \), the diameter of remnant when SNR physical state transfers from Sedov phase to radiative phase, according to formulae (14) and (27), we know

\[
m_\alpha D_t^{-1.5} = m_r D_t^{-2.0}
\]  

(31)

Thus, one gets \( D_t \approx 38 \) pc which is also shown in Fig. 2.

Through statistics, Clark & Caswell (1976) got the diameter at broken point about 32 pc for 29 galactic SNRs at 408 MHz, and also 32 pc at 5000 MHz. Allakhverdiyev et al. (1983) got \( D_t \approx 30 \) pc at 408 MHz for 15 shell-type remnants, and \( \sim 32 \) pc at 1 GHz. For a larger number of samples of 146 all-sort galactic objects including plerion, shell and composite-type remnants, Allakhverdiyev et al. (1985) obtained \( D_t \sim 40 \) pc at 1 GHz. Our result by theoretical analysis method is in somewhat good consistency with theirs. But some authors plotted only a straight line by their statistics early (Duric & Seaquist 1986; Guseinov et al. 2003).

Obviously the \( D_t \) value is the average one of the diameter of all galactic SNRs. When the density \( n_0 \) of interstellar media or magnetic field strength \( (B) \) is somewhat larger than usual, or so, then the transformation diameter \( D_t \) may be smaller, and vice-versa.

Fig. 2.— Comparison plots of some results derived from Case & Bhattacharya (1998), Xu et al. (2005) and on theoretical and statistical ones in this paper. The best fit values are \( \beta = -2.64, -1.6, -1.5/ -2.0 \) (for Sedov/radiative phase) and \(-2.15 (\Sigma \propto D^3) \), respectively. All of the fit lines are somewhat flatter than those derived by some authors at early time.

4. Discussion

4.1. Results comparison

Comparison of some results derived from Case & Bhattacharya (1998), Xu et al. (2005) and on theoretical and statistical ones in this paper was made in Fig. 2. The best fit values are \( \beta = -2.64, -1.6, -1.5/ -2.0 \) (for Sedov/radiative phase) and \(-2.15 (\Sigma \propto D^3) \), respectively. All of the fit lines are somewhat flatter than those derived by some authors at early time.

Case & Bhattacharya (1998) got one straight
slightly steeper line
\[ \Sigma(D) = 5.43 \times 10^{-17} D^{-2.64} \]
\[ (W m^{-2} H z^{-1} s r^{-1}) \] (32)

And Xu et al. (2005) derived a straight flatter line
\[ \Sigma(D) = 1.21 \times 10^{-18} D^{-1.60} \]
\[ (W m^{-2} H z^{-1} s r^{-1}) \] (33)

The best fit line also shows no broken in our new statistics of this paper. Broken in our theoretical analysis is to some extent very small.

4.2. SNR total fluxes increase with age at Sedov-phase?

The radio surface brightness of a remnant defined as
\[ \Sigma = \frac{S_{1 \text{GHz}}}{\theta^2} \] (34)

Here, \( S_{1 \text{GHz}} \) is the detected flux of a remnant at 1 GHz, \( \theta \) is the observational angle.

And we know
\[ \theta^2 \propto D^2 \] (35)

Therefore one has
\[ \Sigma \propto S_{1 \text{GHz}} D^{-2} \] (36)

Let us suppose that
\[ S_{1 \text{GHz}} = S_{0,1 \text{GHz}} D^{\beta'} \] (37)

Where, \( S_{0,1 \text{GHz}} \) is the SNR original flux at 1 GHz, \( \beta' \) is an index of the formula above.

Then
\[ \Sigma \propto D^{-(2-\beta')} = D^{-\beta} \] (38)

Namely \( \beta = 2 - \beta' \)

Now we can see that

1. If \( \beta' = 0 \), then \( \Sigma \propto D^{-2}, \beta = 2, S_{1 \text{GHz}} = S_{0,1 \text{GHz}} \) and \( \Sigma \propto D^{-2} \). It means that the radio flux of a evolved SNR remains a constance.

2. If \( \beta' < 0 \), then \( \beta > 2, S_{1 \text{GHz}} < S_{0,1 \text{GHz}} \). In the case, the flux of a evolved remnant decreases with age.

3. But if \( \beta' > 0 \), then \( \beta < 2, S_{1 \text{GHz}} > S_{0,1 \text{GHz}} \). The evolved remnant flux increases against time.

Our theoretical outcome and a statistical result (Xu et al. 2005) (\( \beta' = 0.50 \) and \( 0.40 \)) are belong to the last case, i.e. the SNR radio flux increases with age. But our statistics in the paper shows \( \beta' < 0 \). In summary, we are not very certain whether the SNR total fluxes increase or decrease with age at Sedov-phase. In other words, the \( \Sigma-D \) relation is not significantly sensitive to be used to determine the variety of SNR radio fluxes.

5. Conclusion

From the basic publicly accepted formulae and some simple reasonable physical suggestions, we derived mathematically the relation between surface brightness and linear diameter of Galactic shell-type SNRs. Firstly, we did a simple statistics about the \( \Sigma-D \) relation of 57 Galactic remnants. The diameter at phase-transition from adiabatic-stage to radiative-stage is also arithmetically obtained and ultimately in agreement with the statistical results gained before. The line slope values in theoretical relation plot are \( \beta = -1.5/-2.0 \) for Sedov/radiative phase (\( \Sigma \propto D^{\beta} \)) respectively. Different statistical results derived now and before were compared with our theoretical one. It shows that all the best fit lines in plots are somewhat flatter than those derived by some authors earlier. One can guess that even the undertook samples of galactic SNRs increase in the future, our statistical outcome of the \( \Sigma-D \) relation will alter a rather little. And also our theoretical result on the relation can by and large remain valuable. Moreover, newly better methods to determine the distance of a common supernova remnant are greatly needed.

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Table 1

Some physical parameters of 57 shell-type Galactic SNRs.

| Source   | Age$^a$  | Dist.$^a$ | Dia.$^b$ size | $S_{1GHz}^c$ | Ref.     |
|----------|----------|-----------|---------------|-------------|----------|
| G4.5+6.8 | 380      | 2900      | 3             | 3           | 19       | H90, G04a |
| G7.7−3.7 | −        | 4500      | 29            | 22          | 11       | M86      |
| G8.7−0.1 | 15800    | 3900      | 51            | 45          | 80       | G96      |
| G18.8+0.3| 16000    | 14000     | 57            | 17x11       | 33       | D99, G04a|
| G27.4−0.0| 2700     | 6800      | 8             | 4           | 6        | C82, G04a|
| G31.9−0.0| 4500     | 7200      | 13            | 7x5         | 24       | CS01     |
| G32.8−0.1| −        | 7100      | 35            | 17          | 11       | K98b     |
| G33.6+0.1| 9000     | 7800      | 23            | 10          | 22       | S03, SV95, G04a |
| G39.2−0.3| 1000     | 11000     | 22            | 8x6         | 18       | C82      |
| G41.1−0.3| 1400     | 8000      | 8             | 4.5x2.5     | 22       | C82, B82, C99 |
| G43.3−0.2| 3000     | 10000     | 10            | 4x3         | 38       | L01      |
| G49.2−0.7| 30000    | 6000      | 52            | 30          | 160      | KK95, G04a |
| G53.6−2.2| 15000    | 2800      | 24            | 33x28       | 8        | S95, G04a |
| G55.0+0.3| 110000   | 14000     | 71            | 20x15?      | 0.5      | MWT98    |
| G65.3+5.7| 14000    | 1000      | 78            | 310x240     | 52       | LRH80, R81 |
| G73.9+0.9| 10000    | 1300      | 8             | 22         | 9        | L89, LLC98 |
| G74.0−8.5| 14000    | 400       | 23            | 230x160     | 210      | LGS99, SI01, G04a |
| G78.2+2.1| 50000    | 15000     | 26            | 60          | 340      | LLC98, KH91 |
| G84.2−0.8| 11000    | 4500      | 23            | 20x16       | 11       | MS80, M77, G04a |
| G89.0+4.7| 19000    | 800       | 24            | 120x90      | 220      | LA96     |
| G93.3+6.9| 5000     | 2200      | 15            | 27x20       | 9        | L99, G04a |
| G93.7−0.2| −        | 1500      | 35            | 80          | 65       | UKB02    |
| G109.1−1.0|17000    | 3000      | 24            | 28          | 20       | FH95, HHv81, G04a |
| G111.7−2.1|320     | 3400      | 5             | 5           | 2720     | TFv01    |
| G111.4+0.3|41000    | 700       | 15            | 90x55       | 6        | MBP02, G04a |
| G116.5+1.1|280000   | 16000     | 32            | 80x60       | 11       | RB81, G04a |
| G116.9+0.2|44000    | 1600      | 16            | 34          | 9        | KH91, G04a |
| G119.5+10.2|24500   | 1400      | 37            | 90?         | 36       | M00      |
| G120.1+1.4|410      | 2300      | 5             | 8           | 56       | H90, G04a |
| G127.1+0.5|85000    | 5250      | 69            | 45          | 13       | FRS84    |
| G132.7+1.3|21000    | 2200      | 51            | 80          | 45       | GTG80, G04a |
| G156.2+5.7|26000    | 2000      | 64            | 110         | 5        | RFA92    |
| G160.9+2.6|7700    | 1000      | 38            | 140x120     | 110      | LA95     |
| G166.0+4.3|81000    | 4500      | 57            | 55x35       | 7        | L89, KH91, G04a |
| G166.2+2.5|150000   | 8000      | 186           | 90x70       | 11       | RLV86    |
| G182.4+4.3|3800     | 3000      | 44            | 50          | 1.2      | KFR98    |
| G205.5+0.5|50000    | 1600      | 102           | 220         | 160      | CB99     |
| G206.9+2.3|60000    | 7000      | 102           | 60x40       | 6        | L86      |
| G206.3−3.4|3400    | 2200      | 35            | 60x50       | 130      | B94, RG81 |
| G266.2−1.2|680      | 1500      | 52            | 120         | 50       | K02, AIS99 |
| G272.2−3.2|6000     | 1800      | 8             | 15?         | 0.4      | D97      |
| G284.3−1.8|10000    | 2900      | 20            | 24?         | 11       | RM86     |
| Source       | Age\(^a\) yr | Dist.\(^a\) pc | Dia.\(^b\) pc | size  | \(S_{1GHz}\) Jy | Ref.    |
|-------------|-------------|----------------|--------------|-------|----------------|---------|
| G296.5+10.0 | 20000       | 2000           | 44           | 90x65 | 48             | MLT88   |
| G296.8−0.3  | 1600000     | 9600           | 47           | 20x14 | 9              | GJ95, G04a |
| G299.2−2.9  | 5000        | 500            | 2            | 18x11 | 0.5            | SVH96   |
| G309.2−0.6  | 2500        | 4000           | 16           | 15x12 | 7              | RHS01   |
| G315.4−2.3  | 2000        | 2300           | 28           | 42    | 49             | DSM01, G04a |
| G321.9−0.3  | 2000000     | 9000           | 70           | 28    | 13             | SFS89, S89 |
| G327.4+0.4  | –           | 4800           | 29           | 21    | 30             | SKR96, WS88, G04a |
| G327.6+14.6 | 980         | 2200           | 19           | 30    | 19             | SBD84, G04a |
| G330.0+15.0 | –           | 1200           | 63           | 180?  | 350            | K96     |
| G332.4−0.4  | 2000        | 3100           | 9            | 10    | 28             | CDB97, MA86, G04a |
| G337.2−0.7  | 3250        | 15000          | 26           | 6     | 2              | RHS01   |
| G337.8−0.1  | –           | 12300          | 27           | 9x6   | 18             | K98b    |
| G346.6−0.2  | –           | 8200           | 19           | 8     | 8              | K98b, D93 |
| G349.7+0.2  | 14000       | 14800          | 9            | 2.5x2 | 20             | RM01, G04a |
| G352.7−0.1  | 2200        | 8500           | 17           | 8x6   | 4              | K98a    |

\(^a\)Notes: Many of the radio SNRs have more than one published value for distance and age. For these, we either chose the most recent estimates or used an average of the available estimates, or the most commonly adopted value.

\(^b\)Notes: Diameters were calculated using from distances together with the angular sizes in Green (2006) catalogue.
REFERENCES

Allakhverdiyev A.O., Amnuel P.R., Guseinov O.H., Kasumov F.K., 1983, Ap&SS, 97, 287

Allakhverdiyev A.O., Guseinov O.H., Kasumov F.K., Yusifov I.M., 1985, Ap&SS, 121, 21

Arbutina B., Urosevic D., Stankovic M., Tesic Lj., 2004, MNRAS, 350, 346

Aschenbach B., Iyudin A.F., Schönfelder V., 1999, A&A, 350, 997 (AIS99);

Berthiaume G.D., Burrows D.N., Garmire G.P., Nousek J.A., 1994, ApJ, 425, 132 (B94)

Binette L., Dopita M.A., Dodorico S., Benvenuti P., 1982, A&A, 115, 315 (B82)

Carter L.M., Dickel J.R., Bonans D.J., 1997, PASJ, 109, 990 (CB99)

Clark D.H., Caswell J.L., 1976, MNRAS, 174, 267

Case G.L., Bhattacharya D., 1998, ApJ, 504, 761

Case G., Bhattacharya D., 1999, ApJ, 521, 246 (CB99)

Caswell J.L., Haynes R.F., Milne D.K., Wellington K.J., 1982, MNRAS, 200, 1143 (C82)

Chen Y., Slane P.O., 2001, ApJ, 563, 202 (CS01)

Chen Y., Sun M., Wang Z.R., Yin Q.F., 1999, ApJ, 520, 737 (C99)

Dickel J.R., Strom R.G., Milne D.K., 2001, ApJ, 546, 447 (DSM01)

Dubner G.M., Moffett D.A., Goss W.M., Winkler P.F., 1993, AJ, 105, 225 (D93)

Duncan A.R., Stewart R.T., Campbell-Wilson D., Haynes R.F., Aschenbach B., Jones K.L., 1997, MNRAS, 289, 97 (D97)

Duric N., Proceeding 232. WE-Heraeus-Seminar 22-25 May 2000, Bad Honnef, Germany. 179D

Duric N., Seaquist E.R., 1986, ApJ, 301, 308

Fesen R.A., Horford A.P., 1995, AJ, 110, 747 (FH95)

Fürst E., Reich W., Steube R., 1984, A&A, 133, 11 (FR84)

Gaensler B.M., Johnston S., 1995, MNRAS, 277, 1243 (GJ95)

Galas C.M.F., Tuohy L.R., Garmire G.P., 1980, ApJ, 236, L13 (GTG80)

Gorham P.M., Ray P.S., Anderson S.B., Kulkarni S.R., Prince T.A., 1996, ApJ, 458, 257 (G96)

Green D.A., 1984, MNRAS, 209, 449

Green D.A., 2004, arXiv:astro-ph/0411083v1, 3 (G04a)

Green D.A., VizieR On-line Data Catalog 7th/227. Mullard Radio Astronomy observatory, Cambridge, United Kingdom (2004), 2002vCat7227, OG (G04b)

Guseinov O.H., AnKay A., Sezer A., Tagieva S.O., 2003, A&AT, 22, 273G(G03)

Hatsukade I., Tsunemi H., Yamashita K., Koyama K., Asaoka Y., Asaoka I., 1990, PASJ, 42, 279 (H90)

Huang Y.-L., Thaddeus P., 1985, ApJ, 295, L13

Hughes V.A., Harten R.H., van den Bergh S., 1981, ApJ, 246, L127 (HHv81)

Itoh H., 1978, PASJ, 30, 489

Kargaltsev O., Pavlov G.G., Sanwal D., Garmire G.P., 2002, ApJ, 580, 1060 (K02)

Kinugasa K., Torii K., Tsunemi H., Yamauchi S., Koyama K., Dotani T., 1998, PASJ, 50, 249 (K98a)

Knödlseder J., Oberlack U., Diehl R., Chen W., Gehrels N., 1996, A&AS, 120, 339 (K96)

Koo B.C., Heiles C., 1991, ApJ, 382, 204 (KH91)

Koo B.C., Kim K.T., Seward F.D., 1995, ApJ, 447, 211 (KKS95)

Koralesky B., Frail D.A., Goss W.M., Claussen M.J., Green A.J., 1998, ApJ, 116, 1323 (K98b)

Kothes R., Fürst E., Reich W, 1998, A&A, 331, 661 (KFR98)

Lacey C.K., Joseph T., Lazio W., Kassim N.E., Duric N., Briggs D.S., Dyer K.K., 2001, ApJ, 559, 954 (L01)
Landecker T.L., Routledge D., Reynolds S.P., Smegal R.J., Borkowski K.J., Seward F.D., 1999, ApJ, 527, 866 (L99)
Leahy D.A., 1986, A&A, 156, 191 (L86)
Leahy D.A., 1989, A&A, 216, 193 (L89)
Leahy D.A., Aschenbach B., 1996, A&A, 315, 260 (LA96)
Leahy D.A., Aschenbach B., 1995, A&A, 293, 853 (LA95)
Levenson N.A., Graham J.R., Snowden S.L., 1999, ApJ, 526, 874 (LGS99)
Lorimer D.R., Lyne A.G., Camilo F., 1998, A&A, 331, 1002 (LLC98)
Lozinskaya T.A., 1981, Soviet Astron. Lett., 7, 17
Matthews H.E., Baars J.W.M., Wendker H.J., Goss W.M., 1977, A&A, 55, 1 (M77)
Matthews H.E., Shafer P.A., 1980, A&A, 87, 255 (MS80)
Matthews B.C., Wallace B.J., Taylor A.R., 1998, ApJ, 493, 312 (MWT98)
Mavromatakis F., Bounis P., Paleologou E.V., 2002, A&A, 383, 1011 (MBP02)
Mavromatakis F., Papamastorakis J., Paleologou E.V., Ventura J., 2000, A&A, 353, 371 (M00)
Meaburn J., Allan P.M., 1986, MNRAS, 222, 593 (MA86)
Mills B.Y., Turtle A.J., Little A.G., Durding J.M., 1984, Austral. J. Phys., 37, 321
Milne D.K., 1979, Australian J. Phys., 32, 83
Milne D.K., Roger R.S., Kesteven M.J., Haynes R.F., Wellington K.J., Stewart R.T., 1986, MNRAS, 223, 487 (M86)
Poveda A., Waltjer L., 1968, AJ, 73, 65
Ptuskin V.S., Zirakashvili V.N., 2003, A&A, 403, 1
Rakowski C.E., Hughes J.P., Slane P., 2001, ApJ, 548, 258 (RHS01)
Reich W., Braunsfurth E., 1981, A&A, 99, 17 (RB81)
Reich W., Fürst F., Arnal E.M., 1992, A&A, 256, 214 (RFA92)
Reynoso E.M., Mangum J.G., 2001, ApJ, 121, 347 (RM01)
Rosado M., 1981, ApJ, 250, 222 (R81)
Rosado M., González J., 1981, Rev. Mexicana. Astron. Astrophys., 5, 93 (RG81)
Routledge D., Landecker T.L., Vaneldick J.F., 1986, MNRAS, 221, 809 (RLV86)
Ruiz M.T., May J., 1986, ApJ, 309, 667 (RM86)
Saken J.M., Long K.S., Blair W.P., Winkler P.F., 1995, ApJ, 443, 231 (S95)
Salter C.J., Reynolds S.P., Hogg D.E., Payne J.M., Rhodes P.J., 1989, ApJ, 338, 171 (S89)
Seward F.D., Kearns K.E., Rhode K.L., 1996, ApJ, 471, 887 (SKR96)
Seward F.D., Slane P.O., Smith R.K., Sun M., 2003, ApJ, 584, 414 (S03)
Seward F.D., Velusamy T., 1995, ApJ, 439, 715 (SV95)
Shull J.M., Fesen R.A., Saken J.M., 1989, ApJ, 346, 860 (SFS89)
Slane P., Vancura O., Hughes J.P., 1996, ApJ, 465, 840 (SVH96)
Srinivasan G., Bhattacharya D., Dwarakanath K.S., 1984, J. Astrophys. Astr., 5, 403 (SBD84)
Stil J.M., Irwin J.A., 2001, ApJ, 563, 816 (SI01)
Thorstensen J.R., Fesen R.A., van den Bergh S., 2001, AJ, 122, 297 (TFv01)
Uyaniker B., Kothes R., Brunt C.M., 2002, ApJ, 565, 1022 (UKB02)
Völk H.J., Berezhko E.G., Ksenofontov L.T., Rovell G.P., 2002, A&A, 396, 649
Weiler K.W., Sramek R.A., 1988, ARA&A, 26, 295 (WS88)

Xu J. W., Zhang X. Z., Han J. L., 2005, Chinese J. Astron. Astrophys., 5, 165

Zaninetti L., 2000, A&A, 356, 1023