Publl. Astron. Soc. Japan **26**, 399-416 (1974)

Radio Spurs and Spiral Structure of the Galaxy. II. On the Supernova Remnant Hypothesis for Spurs

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(Received 1973 September 12; revised 1973 December 19 and 1974 March 19)

Abstract

A hypothesis that galactic spurs are due to nonthermal emission from supernova shells is shown to meet with some difficulties in the attempt to understand observational data on radio continuum distribution, starlight polarization, X-rays, Hα-emission, λ21-cm line emission, and interstellar dark matter in the spur regions. A galactic shock hypothesis, that the spur is a result of tangential view to diffuse nonthermal source extending just above and along the spiral shocked region of the Galaxy, is more compatible with these observations.

Key words: Galactic shock waves; Galaxy; Radio spurs; Supernova remnants.

1. *Introduction*

A number of galactic spurs run up to higher latitudes from the galactic plane on iso-brightness contour maps of the background of radio continuum of the Galaxy. It has been said that some of the spurs are situated on small circles on the sky (QUIGLEY and HASLAM 1965; HASLAM, QUIGLEY, and SALTER 1970; BERKHUIJSEN, HASLAM, and SALTER 1971). Four circles so far identified are called Loop I (the North Polar Spur; this will be referred to as NPS), Loop II (Cetus Arc), Loops III and IV. In order to account for these distributions of radio continuum, a supernova remnant (SNR) hypothesis has been proposed (HANBURY BROWN, DAVIES, and HAZARD 1960) and is supported by many investigators (see, for example, BERKHUIJSEN, HASLAM, and SALTER 1971).

In addition to the observation of radio brightness distribution of the Galaxy, many other measurements have been made over a wide area of the sky, including a number of radio spurs; up-to-date data have become available for investigating the spurs: they are linear polarization of radio continuum, λ21-cm line emission, optical polarization of starlight, Hα-emission, and diffuse soft X-rays. The North Polar Spur, in particular, has been extensively investigated by making use of these observations.

Recently one of the present authors (SOFUE 1973; this paper will be referred to as Paper I) proposed a new hypothesis for the galactic spurs, that they are due to tangential view to diffuse nonthermal radio source extending just above and along the spiral arm. SOFUE (1973) considers that such a radio source is formed by galactic shock waves at the spiral arm and the subsequent ejection of diffuse plasma, with magnetic fields and cosmic rays, in the z-direction.

The present paper is an attempt to examine the supernova remnant hypothesis on the basis of the recent observations mentioned above and on statistics of supernova remnants (MILNE 1970; ILOVAISKY and LEQUEUX 1972a, b). The galactic shock (GS) hypothesis for the spur proposed in Paper I will be briefly discussed in comparison with the SNR hypothesis.

2. *Geometrical Parameters of a Galactic Loop*

Under the assumption that a galactic loop (spur) is due to nonthermal radio emission from a supernova shell, we begin by obtaining geometrical information about the NPS (Loop I), including the radius and thickness of the shell and the distance from the sun.

(i) *Shell Structure*

The distance to the center of a supernova shell d is represented as $d=r$ cosec $(\theta/2)$, where r is the radius of the shell and θ is the angular diameter of the loop measured at the sun. The characteristic thickness of the shell Δr is determined from the observed half-angular-width $\Delta\theta$ of the spur, and by specifying volume emissivity of radio continuum in the shell. A maximum path length L in the shell on the line-of-sight can be estimated geometrically from r and Δr, $L\approx(8r\cdot\Delta r)^{1/2}$. For the NPS with $\theta=116°$ (BERKHUIJSEN et al. 1971) and $\Delta\theta=10°$, we have $\Delta r=0.05r$ and $L=0.6r$, if the volume emissivity is uniform in the shell. BERKHUIJSEN et al. (1971) noticed that a spur of the λ21-cm line emission of neutral hydrogen (H I) gas is associated in position with the NPS and that its angular diameter is $\theta_{\rm H}=126°$ and its half-angular-width is $\Delta\theta_{\rm H}=5°$, where and hereafter the subscript H is attached to the quantity associated with the neutral hydrogen spur (H I-spur). In the same way as with the NPS we have $\Delta r_{\rm H}=0.034r$ and $L_{\rm H}=0.52r$.

(ii) *Radius of the Shell*

(a) An empirical relation has been obtained between the linear diameter D of supernova remnants and their surface brightness Σ at 1 GHz (a Σ–D relation; ILOVAISKY and LEQUEUX [1972a]). BERKHUIJSEN (1973a) has estimated the average surface brightness of Loop I at 1 GHz by using radio data compiled from different frequencies and assuming a spectral index $\alpha=0.7\pm0.2$. BERKHUIJSEN (1973b) estimates the diameter of Loop I as $D=35$ to 140 pc by applying the Σ–D relation due to ILOVAISKY and LEQUEUX (1972a) to this loop. Then we have $17<r<70$ pc.

(b) Hydrogen mass in the shell is $M_1=4\pi r^2\Delta r_{\rm H} n_{\rm H} m_{\rm H}$. If interstellar gas has been swept up into the shell through a snow-plow effect (SPITZER 1968), the total mass of hydrogen gas in the shell will be $M_2=(4\pi/3)r^3 n_{\rm H0} m_{\rm H}$ and $M_1\leq M_2$, where $n_{\rm H0}$ and $n_{\rm H}$ are the number densities of neutral hydrogen in the normal interstellar space and in the H I shell, respectively. The inequality $M_1\leq M_2$ leads to $r\geq 0.2N_{\rm H}/n_{\rm H0}$ for the NPS, where $N_{\rm H}$ is an observed excess of column density of neutral hydrogen in the spur region over the background, and the relations in section 2(i), $\Delta r_{\rm H}=0.034r$ and $L_{\rm H}=0.52r$ are used. When $n_{\rm H0}=1\,{\rm cm}^{-3}$ and $N_{\rm H}=2\times 10^{20}\,{\rm cm}^{-2}$ at $b=20°$ (see TOLBERT 1971), we obtain a rough lower limit on r, or $r\geq 13$ pc.

(c) If the H I-spur associated with the NPS is due to shock compression of interstellar neutral hydrogen, we have $n_{\rm H0}<n_{\rm H}=N_{\rm H}/0.52r$ in the shell. As in the previous subsection we have a rough upper limit on r, or $r<130$ pc.

(d) If it is true that the loop ridge lies on a small circle on the sky and if the H I-spur is associated with the NPS, the supernova shell should be located

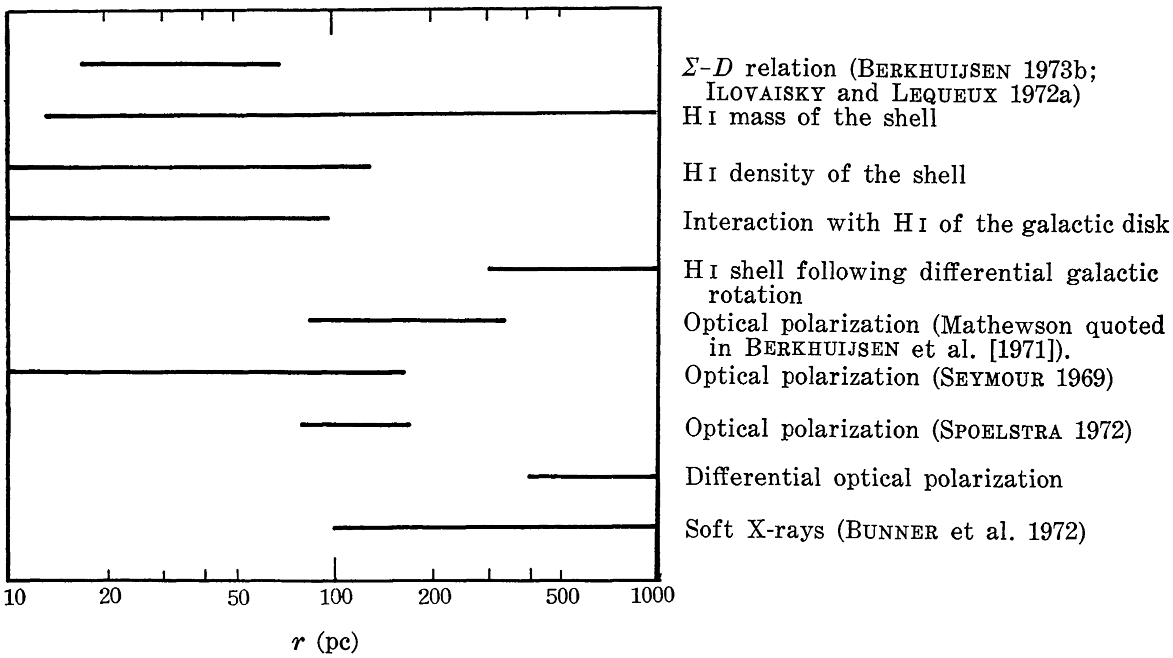

Fig. 1. Summary of various estimates of the radius of Loop I. The loop is assumed to be a supernova remnant.

well within the gas layer of the Galaxy. If the radius of the shell is comparable with or larger than the thickness of the gas layer, the shell would be deformed during its propagation through the medium with magnetic field and with appreciable density gradient in the z-direction. Thus, we can expect that the diameters of the Loops I to IV must be smaller than 100 pc. This is, of course, only a tentative conclusion because the deformation of an SNR shell in the galactic disk has never been worked out in detail (see also KAFATOS and MORRISON [1973]).

Figure 1 summarizes the various estimates of the radius of the shell made so far, together with other estimates obtained from diffuse X-ray observations (BUNNER, COLEMAN, KRAUSHAAR, and McCAMMON 1972), from motion of H I gas (section 5) and from optical polarization measurements of stars (section 6; SPOELSTRA 1972). From data of optical polarization, SEYMOUR (1969) and Mathewson (quoted in BERKHUIJSEN et al. [1971]) conclude respectively $r<170$ pc and $80<r<340$ pc. These two estimates are also shown in figure 1. In this figure we find that no definite determination can be made for the radius of Loop I. Some of the above estimates seem to contradict each other, so far as we assume the galactic loop to be a supernova shell. It should be remembered, however, that the limits of these estimates cannot be very strict and that none of these is good enough to rule out any of the others completely. It should be also noted that the maximum diameter of a remnant whose expansion velocity drops below the turbulent velocity of the interstellar gas ($\sim$10 km s^{-1}) is about 110 pc ($r=55$ pc) (ILOVAISKY and LEQUEUX 1972b), and an SNR with radius larger than 55 pc will disappear.

We will take up in the next sections the following two typical cases for the radius of the shell responsible for the galactic loops. One is $r=10$ to 30 pc, and the other $r=100$ to 150 pc. The former case suggests that the loop is a fragment of an old, normal SNR such as the Cygnus Loop, and the latter an extremely old SNR or a super-supernova remnant (SSNR) as proposed by BINGHAM (1967).

3. *Distribution of SNRs and Probability of Finding Them as Spurs*

The probability of finding supernova remnants as galactic spurs has been briefly discussed by HANBURY BROWN et al. (1960), SHKLOVSKY (1968), and in Paper I. We estimate it in some detail and discuss the distribution of SNRs in the solar vicinity on the basis of more recent data.

(i) *Distribution of SNRs on the Galactic Plane*

From the data on SNRs given by ILOVAISKY and LEQUEUX (1972a) we plot linear diameters of SNRs versus their distances from the sun (figure 2). Loops I to IV are also given, whose linear diameters are determined from the Σ–D relation and the average brightness Σ estimated by BERKHUIJSEN (1973a). The apparent

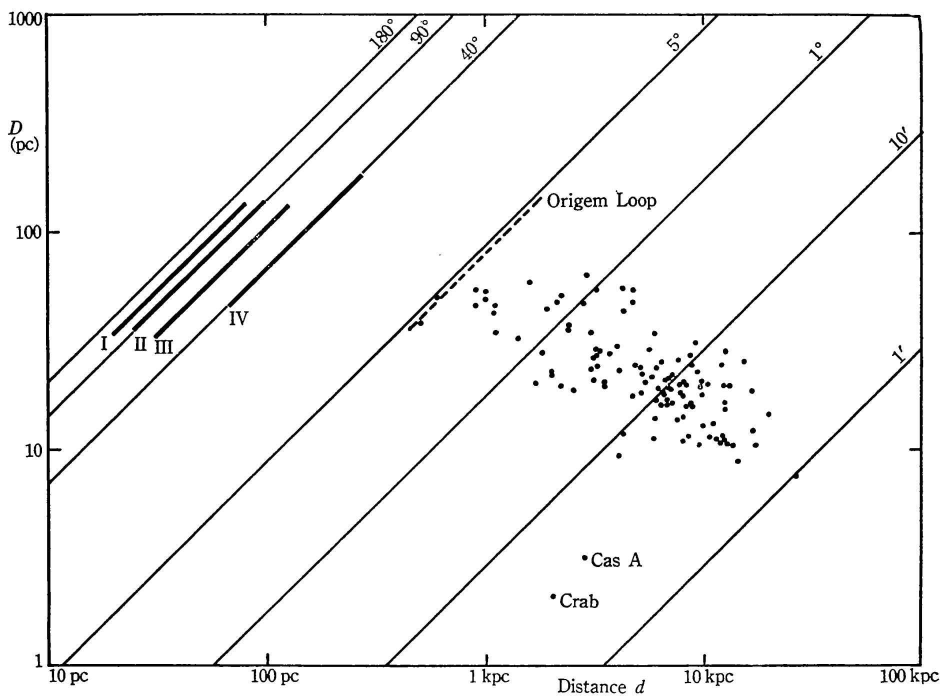

Fig. 2. Linear diameters D of SNRs plotted against their distances d from the sun. The data are due to ILOVAISKY and LEQUEUX (1972a). The Origem Loop (SPOELSTRA 1973) is also given with the dashed line.

angular diameters can be read from the numbers on the tilted lines in the figure. A clear lack of SNRs is found between the apparent diameters of 5° and 40° in the distribution diagram, if Loops I to IV are SNRs. This figure shows that the number density of SNRs seems unusually high within 100 pc of the sun. Even if a selection effect in radio surveys (ILOVAISKY and LEQUEUX 1972a; see the next subsection) is taken into account, such a frequent occurrence of nearby SNRs with extremely large angular diameters of 40° to 120° remains difficult to explain.

(ii) *Probability of Finding Four SNRs in the Solar Vicinity*

ILOVAISKY and LEQUEUX (1972a) showed a new selection effect for large-diameter SNRs (D>30 pc), which effectively reduces the number of such objects detected in radio surveys, and they determined an "integral luminosity function" for SNRs. The characteristic distribution of Loops I to IV in figure 2 may represent this selection effect.

On the basis of ILOVAISKY and LEQUEUX's (1972a) diagram for the number of SNRs having a linear diameter smaller than D pc, $N(<D)$, we can estimate the probability of finding four SNRs with diameter smaller than 50 pc in the solar neighborhood. The number of SNRs with $D<50$ pc, after correction for the limiting-flux selection effect, is $N=62$ within 6.3 kpc of the sun. Suppose SNRs are randomly distributed over the galactic plane, then the probability of finding four SNRs within d pc of the sun is given by $w=(m^4/4!)\exp(-m)$, where $m=Nd^2/(6300)^2$. We can obtain immediately $m=3.9\times10^{-3}$ and $w=0.96\times10^{-11}$ for $d=50$ pc, and $m=1.56\times10^{-2}$ and $w=2.5\times10^{-9}$ for $d=100$ pc.

The integral luminosity function, $N(<D)$, can be represented by a power-law approximation in the range $10<D<30$ pc (ILOVAISKY and LEQUEUX 1972a). If this approximation holds for SNRs with diameter larger than 30 pc and up to 50 pc, then N amounts to 150 within 6.3 kpc of the sun. In the same way as discussed just above, we have $w=3.3\times10^{-10}$ for $d=50$ pc, and $w=8.5\times10^{-8}$ for $d=100$ pc. In view of figure 2 of ILOVAISKY and LEQUEUX (1972a) and figure 1 of ILOVAISKY and LEQUEUX (1972b) these probabilities are regarded as upper limits. Thus such an extremely small value for w concludes that the SNR hypothesis is less convincing if Loops I to IV are due to SNRs with diameters of 50 pc or less. If the Loops are SSNRs or SNRs with radii of 100 pc or more, we cannot apply this method to obtain the probability w. The existence of SSNRs or SNRs with radii of 100 pc or more has never been established to provide basic data for statistics (see ILOVAISKY and LEQUEUX 1972a).

(iii) *Contribution of SNRs to the Background Radio Continuum*

If the galactic loops are due to old SNRs with radii of 100 pc to 150 pc and if such SNRs are distributed over the galactic plane with an equal concentration to that in the solar vicinity, the contribution of such SNRs to the galactic radio continuum would amount to about sixty percent of the nonthermal disk component at 820 MHz (BERKHUIJSEN 1971). If this is the case in spiral galaxies, and if the pattern theory on spiral arms (LIN and SHU 1964; LIN 1970) and the galactic shock wave theory (FUJIMOTO 1966; ROBERTS 1969; ROBERTS and YUAN 1970; TOSA 1973a) are correct, the nonthermal radio emission from luminous arms should be much stronger than from other regions. Birth of stars and their final supernova explosions must occur frequently in the luminous arms. However, MATHEWSON, KRUIT, and BROUW (1972) show that radio-bright arms of M51 are located not along the luminous arms but along the dark lanes. This observation is, though not directly, contradictory to the assumption that the spurs are due to old SNRs with linear diameters of 100 pc or more.

From his observation on M31 at 408 MHz and 1407 MHz, POOLEY (1969) has found some radio-bright arms in a good spatial coincidence with the distribution of H II regions. The radio component is shown to be nonthermal from its spectral index. If we look in more detail at POOLEY's (1969) map of radio-brightness distribution, however, we find that some of the radio-bright arms are clearly located along the dark lanes on the concave side of the optically luminous arm. The above conclusion obtained in M51 seems to hold in M31.

4. *Optical and X-Ray Observations of Spur Regions*

(i) *Dark Matter Associated with Galactic Spurs*

A positional correlation has been found between some of the galactic spurs and dark regions in the Milky Way (Paper I). A large dark region at $l=20°$ to $35°$, $b=0°$ to $10°$ is closely associated with the NPS. We examine whether such a large obscured region can be produced by interaction of an SNR with interstellar gas.

A photo-electric observation of diffuse starlight in the Milky Way was made by ELSÄSSER and HAUG (1960). It is shown that the diffuse starlight at the bottom of the NPS or at $l=20°$ to $35°$ and $b=0°$ to $10°$ is obscured by 0.75 mag (at $b=10°$), compared with normal regions at the same latitude. If we attribute this obscuration directly to an SNR shell, which is responsible for the NPS, then the extinction coefficient in the shell is $\kappa=0.75\,\mathrm{mag}/L$, where L is the path length on the line-of-sight in the shell. If the radius of the SNR is 20 to 100 pc, the path length in

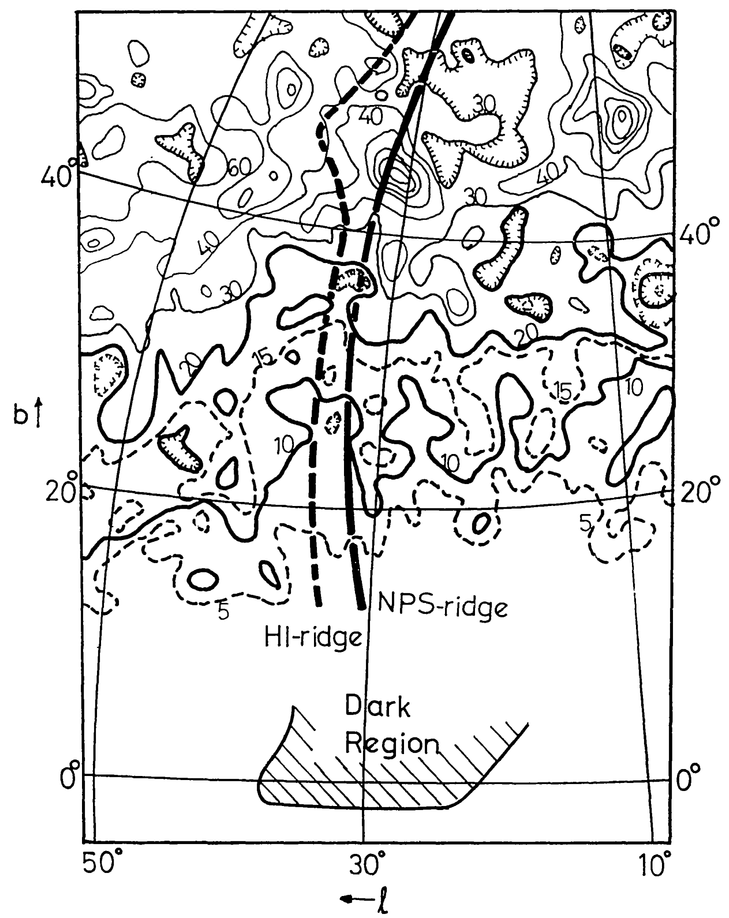

Fig. 3. Distribution of galaxies observed around the NPS. The data are due to SHANE and WIRTANEN (1967). Numerals on contour lines indicate the number of galaxies per square degree. Thick contour lines indicate 10 and 20 galaxies per square degree. The shaded area is the large dark region in the Milky Way. The ridges of the NPS of radio continuum and of the H I-spur are shown with the heavy solid and dashed lines, respectively. High number densities of galaxies at $l\approx32°$, $b\approx44°$ and at $l\approx7°$, $b\approx48°$ are due to clusters of galaxies.

the shell is 10 to 50 pc. We have $\kappa=15$ to 75 mag kpc^{-1}, which is 15 to 150 times as great as $\kappa_0=0.5$ to 1 mag kpc^{-1} in the normal region. Such an unusually high concentration of obscuring matter cannot be attributed to a supernova shell.

If the dark region or the position of obscuring matter coincides accidentally with the bottom or ridge of the NPS on the line-of-sight, the above discussion gives only an upper limit on κ. In order to see whether or not the dark region observed at $l=20°$ to $35°$ and $b=0°$ to $10°$ is accidentally associated with the NPS, we reproduce in figure 3 a distribution map of galaxies from SHANE and WIRTANEN (1967). Iso-density lines representing 10 to 30 galaxies observed per square degree rise up to $b=30°$ to $40°$, and the ridge of the iso-contour lines is located at the H I-spur ridge and slightly apart from the continuum ridge of the NPS. The obscuring matter must coexist together with the H I gas.

As shown in Paper I, some other dark regions are associated in position with some galactic spurs. We give a good example for the coincidence between H I-spur and dark matter: A large H I-spur emerges from the galactic plane down to $b=-60°$ in the longitude range $l=170°$ to $190°$. In the same region, $b=-10°$ to $-50°$, $l=170°$ to $190°$, galaxies are strongly obscured (SHANE and WIRTANEN 1967). From these two cases, we can conclude that the dark region at $l=20°$ to $35°$ in the Milky Way must be physically associated with the NPS and the discussion in the present section would be the actual cases.

A diffuse starlight distribution has been calculated on the basis of the GS hypothesis (Paper I). Some dark regions in the Milky Way and their associated spurs of radio continuum are reproduced. In this calculation we have taken a path length $L=0.5$ to 1 kpc in the interarm bridge ($l\approx30°$) linking the Cygnus and Sagittarius arms. An excess of the extinction coefficient due to the bridge is then 0.75 to 1.5 mag kpc^{-1}. This quantity can be understood as due to a concentration of interstellar gas at the bridge and the subsequent ejection of gas in the z-direction (Paper I).

(ii) *Hα Emission*

If the galactic loops are due to SNRs with $r<50$ pc we might observe Hα emission from them as in the Cygnus Loop. Only very weak Hα emission is, however, observed at the ridge of the NPS, $b=10°$–$25°$, where the brightness temperature at 408 MHz is 50 to 60 K (SEEGER, WESTERHOUT, CONWAY, and HOEKEMA 1965). This brightness temperature is sufficiently comparable with the maximum brightness temperature at 430 MHz of the Cygnus Loop, $T_b=65$ to 70 K, where the Hα emission is strong (KUNDU and VELUSAMY 1967). DAVIES, HANBURY BROWN, and MEABURN (1963) have obtained an upper value of the Hα emission from the NPS region as

$$(I_{\mathrm{H}\alpha}/I_{\mathrm{R}})_{\mathrm{NPS}}/(I_{\mathrm{H}\alpha}/I_{\mathrm{R}})_{\mathrm{Cygnus\ Loop}}<0.002\text{–}0.008\ ,$$

where $I_{\mathrm{H}\alpha}$ and I_{R} are the Hα intensity and radio intensity at 240 MHz, respectively. Such a very weak Hα emission from the NPS has been a long standing difficulty since HANBURY BROWN et al. (1960) proposed the SNR hypothesis for the spur. Recently, HASLAM, KAHN, and MEABURN (1971) reported that a faint Hα nebulosity was detected on the ridge of the NPS, while no quantitative discussion was made in their paper.

MEABURN (1965, 1967) and ELLIOTT (1970) observed some diffuse Hα nebulosities and filaments ($l=180°$–$210°$, $b=-30°$–$-40°$; $l=160°$–$200°$, $b=-30°$–$-40°$; $l=120°$–$160°$, $b=60°$–$65°$; $l=60°$, $b=50°$–$60°$) near Loops II and III. A diffuse nebulosity ($l=40°$-$50°$, $b=-30°$-$-50°$) is also observed just on the ridge of Loop II (HASLAM et al. 1971). MEABURN (1965, 1967) and ELLIOTT (1970) concluded that the Hα emission is associated with the nearby loops and that the SNR hypothesis was supported observationally.

However a question still exists whether the association is physical or accidental, because the search for the Hα nebulosities has been made only within relatively narrow regions along the loops. This question should be answered through a statistical test when an extensive survey of Hα nebulosities and filaments has been made over a large area of the sky (particularly at $|b|\gtrsim 30°$). Another question is why some Hα emitting regions are located on the loop and others are $\sim 20°$ apart from the spur ridge. Such various locations of the nebulosities cannot be interpreted coherently through a theory of supernova remnants. We still, therefore, hesitate to accept the SNR hypothesis.

If the Hα nebulosities are really due to the spurs, the GS hypothesis meets with a difficulty in interpreting the Hα emission. No mechanism to emit the observable amount of Hα photons is known to exist in the galactic shock wave.

(iii) *X-Rays from Spur Regions*

Diffuse soft X-rays have been detected in the NPS region (BUNNER, COLEMAN, KRAUSHAAR, and MCCAMMON 1972). A spur-like distribution (which will be hereafter referred to as X-ray NPS) is found in iso-contour maps of the X-ray intensity in the energy ranges of $E\approx 0.28$ keV and $0.5<E<1$ keV. According to BUNNER et al. (1972), the diffuse soft X-rays from the NPS region are galactic in origin, because the interstellar gas with the column density of neutral hydrogen in this direction, $N_H \approx 4\times 10^{20}$ H cm^{-2} ($b=30°$), is sufficiently dense to absorb a significant part of the extragalactic soft X-rays. DAVIDSEN, SHULMAN, FRITZ, MEEKINS, HENRY, and FRIEDMAN (1972) have made an observation of background X-rays at 0.28 keV, covering a wide region of the sky including Loop III. They found no X-ray enhancement along the loop-ridge, and found no support for the SNR hypothesis for Loop III.

The observation by BUNNER et al. (1972) shows that the X-ray intensity of the NPS is about 10^{-2} times that of the Cygnus Loop. The observation also indicates that the X-ray NPS is located not on the ridge but on the innermost (concave) side of the NPS. Such a structure in brightness distribution could not be expected of a supernova shell; if the NPS is produced by shock compression of interstellar gas, the temperature must be highest on the ridge of the NPS and, therefore, the X-ray spur should coincide spatially with the NPS.

If the X-rays from the NPS are of thermal origin, the temperature is 3–5×10^6 K. As will be discussed in the next section, the expansion velocity of the neutral hydrogen shell responsible for Loop I is less than 19 km s^{-1}, which is not enough to heat the gas up to this high temperature. Thus it is not easy to account for the X-ray NPS by a supernova shell.

If the interarm bridge linking the Cygnus and Sagittarius arms ($l=30°$) is due to a galactic shock wave, the interstellar gas enters the shock front with a velocity of 100 km s^{-1} or so. This velocity is a little too low to heat the gas up to such a high temperature. The GS hypothesis cannot explain the X-ray NPS.

5. *Motion of Neutral Hydrogen Gas at Galactic Spurs*

(i) *Do the Loops Follow the Differential Rotation of the Galaxy?*

McGee, Murray, and Milton (1963) give contour maps of the peak brightness temperature of profiles of low velocity neutral hydrogen. From this map Berkhuijsen, Haslam, and Salter (1971) found an H I-spur lying at $l=35°$ to $40°$, $b=10°$ to $65°$ on the convex side of the NPS of radio continuum. The axis of the H I-spur is about 5° apart from that of the NPS. Grahl, Hachenberg, and Mebold (1968) carried out an observation of H I gas along a fixed galactic latitude ($b=30°$), and obtained a distribution map of radial velocity as a function of the galactic longitude (v_r-l diagram). Using the map of Grahl et al. (1968), Berkhuijsen et al. (1971) found that H I gas with high velocity dispersion is associated with the NPS (of radio continuum). They also pointed out that the same structure is observed at Loop III ($l\approx95°$, 155°) and diametrically opposite to the NPS ($l\approx265°$).

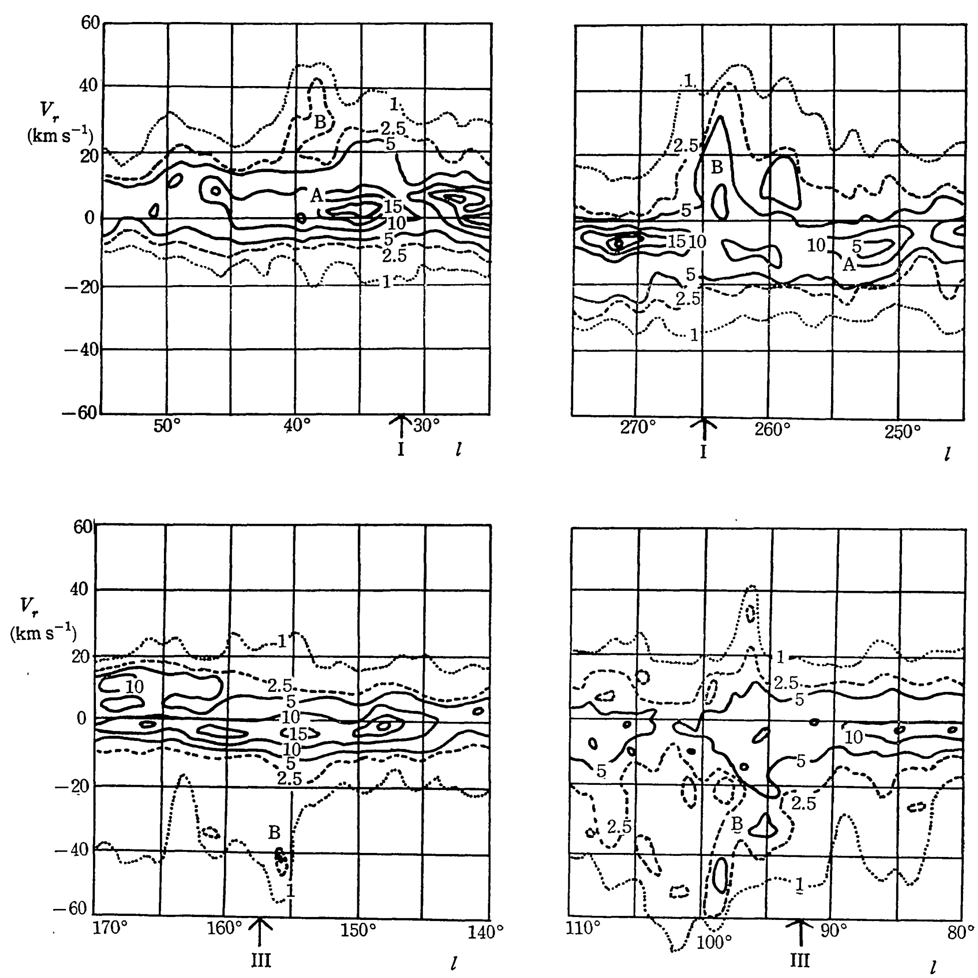

Fig. 4. Density distributions of neutral hydrogen gas in the l-v_r coordinate system (Grahl et al. 1968), where v_r is the radial velocity. Concentrations of neutral hydrogen gas are found at $l=35°$, 80°, 150°, and 252°, close to some prominent galactic spurs. Positions of Loops I and III of radio continuum are indicated with arrows.

Figure 4 is the (v_r–l) diagram of H I gas reproduced from GRAHL et al. (1968). The H I-spur found at l=35° to 40° consists of two components, i.e., a "narrow" component with low velocity dispersion (A in figure 4) and a "flat" component with high dispersion (B). The H I-spur observed at l=35° to 40° and b=30° is mainly due to the narrow component A. According to FEJES and WESSELIUS (1973), the part diametrically opposite to the H I-spur at the NPS would be identical with a concentration of gas at l=250° to 252° (component A in figure 4), where an H I-spur is observed to rise up to $b \approx 65°$.

The radial velocity observed at the maximum brightness at l=35° and that at l=252° is $+3\,\mathrm{km\,s^{-1}}$ and $-8\,\mathrm{km\,s^{-1}}$, respectively. Their sense and magnitude are rather in agreement with a large scale, systematic motion of gas (see the double-sine curve in figure 12 of GRAHL et al. [1968]). From these facts we conclude that the neutral hydrogen gas associated with the spurs is following the local differential rotation of the Galaxy. If these radial velocities are caused by an SNR shell sweeping up interstellar gas in galactic differential rotation, the radius of the shell should be greater than several hundred pc.

Since the H I-spur is considered in the GS hypothesis as due to the ejection of gas out of the spiral arm in the z-direction, it is reasonable that the radial velocity of the H I-spur follows the law of galactic rotation. As shown in the distribution diagram of the radial velocity of the gas (figure 11 of GRAHL, HACHENBERG, and MEBOLD [1968]), the narrow component at l=35° takes a somewhat larger velocity compared with the neighboring gas. This component would be contributed from the more distant gas ejected out of the galactic plane.

(ii) *Expansion Velocity of the SNR Shell*

If the galactic loop is an SNR shell, the expanding motion will give rise to a dispersion in the observed radial velocity of neutral hydrogen gas as $\sigma \approx (L_H/r)V$, assuming a homogeneous shell. Here σ is the velocity dispersion and V is the expansion velocity of the compressed hydrogen gas in the supernova shell. We have estimated $L_H=0.52r$ in section 2(i) for the NPS. FEJES and WESSELIUS (1973) have estimated in roughly the same way $V>65\,\mathrm{km\,s^{-1}}$ for the NPS with $\sigma \approx 40\,\mathrm{km\,s^{-1}}$. This velocity dispersion is mostly due to the flat component (B) at l=38° in figure 4. As discussed in (i) of the present section, we should make use of the velocity dispersion of the narrow component (A) at l=35° rather than that of the flat component (B) at l=38°. In this case, σ=11–14 km s^{-1}, leading to V= 21 to 27 km s^{-1}. If σ is partly caused by a random velocity of interstellar gas of 10 km s^{-1}, V reduces to 9-19 km s^{-1}. In any case, the expanding motion of the shell with such a low velocity cannot heat the gas up to 3–5$\times 10^6$ K to emit the soft X-rays at the NPS.

6. *Differential Polarization of Starlight in the NPS Region*

SPOELSTRA (1971) has made a comparison between starlight polarization in the spur regions and that in the spur-free region. He found neither a significant difference in polarization between these two regions within 300 pc of the sun, nor any enhancement of the degree of polarization at 20–100 pc in the direction of the NPS. In the present section we discuss the distribution of magnetic fields in the NPS region as a function of latitude and distance on the basis of a differential polarization analysis of starlight. The method we take follows LLOYD and HARWIT (1973), and the data of starlight polarization are due to MATHEWSON and FORD

(1970).

The NPS is divided into six areas along its ridge by $b=0°$–$10°$, $10°$–$20°$, $20°$–$30°$, $30°$–$40°$, $40°$–$50°$, and $50°$–$60°$. Each area has a longitudinal spread of $\pm 5°$ from the ridge. In each area, stars up to 4 kpc from the sun are grouped in accordance with their distances; $\delta s_1=0$–50 pc, $\delta s_2=50$–100 pc, $\delta s_3=100$–200 pc, $\delta s_4=200$–400 pc, $\delta s_5=400$–600 pc, $\delta s_6=600$–1000 pc, $\delta s_7=1000$–2000 pc, and $\delta s_8=2000$–4000 pc. The number of stars falling into each unit is 5 to 15.

When starlight travels the i-th distance unit δs_i toward the sun, the Stokes parameters Q and U will increase by δQ_i and δU_i. We approximate the degree of differential polarization in the i-th distance unit by

$$\left(\frac{dP}{ds}\right)_i=\left\{\left(\frac{\delta Q_i}{\delta s_i}\right)^2+\left(\frac{\delta U_i}{\delta s_i}\right)^2\right\}^{1/2},$$

and the position angle χ_i of the plane of polarization intrinsic to the i-th distance unit is represented by

$$\tan 2\chi_i=\frac{\delta U_i}{\delta Q_i},$$

where $\delta Q_i=Q_i-Q_{i-1}$ and $\delta U_i=U_i-U_{i-1}$.

We plot $(dP/ds)_i$ and χ_i in the (x, z)-plane in figure 5 where x and z are given by $x=s\cos\bar{b}$ and $z=s\sin\bar{b}$. Here $\bar{b}$ designates the central value of galactic latitude of each area along the ridge of the NPS. The length of the bar represents the

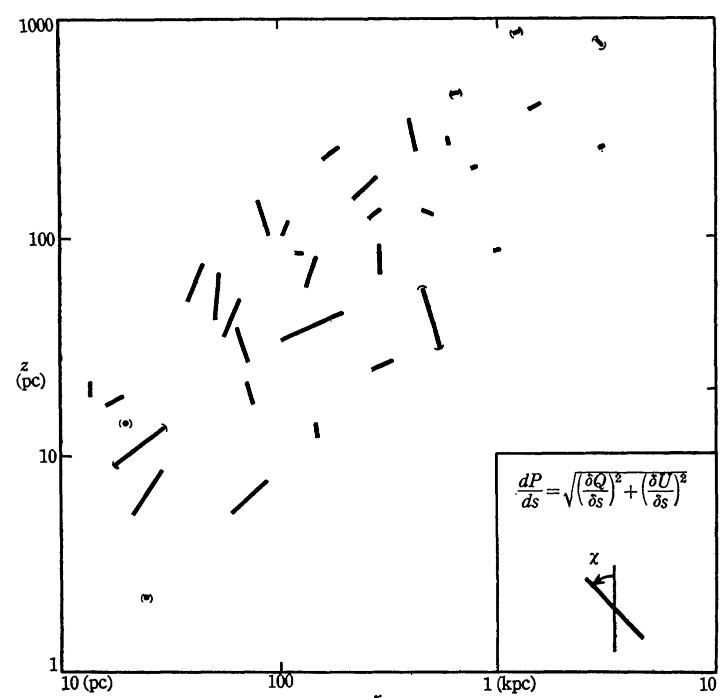

Fig. 5. Distributions of the differential polarization in the NPS region ($l\approx 30°$). The length and tilt of the bars represent the magnitude (in arbitrary units) of the degree of polarization and the position angle of the plane of polarization, respectively, and x- and z-axes are respectively $x=s\sin b$ and $z=s\cos b$, with s the distance to the stars used. Some results with less statistical certainty are indicated with parentheses.

degree of differential polarization in an arbitrary unit and the angle between the bar and the z-axis designates the position angle χ_i.

We find from figure 5 that differential polarization remains nearly constant up to x=500 pc and z=200 pc. [The small degree of polarization for s>1000 pc is probably due to smoothing out by small-scale (<200 pc) magnetic-field structures in the distance units δs_7=1000–2000 pc and δs_8=2000–4000 pc.] The position angle of the plane of polarization in each distance unit is also roughly parallel to the spur ridge, at least up to x=500 pc. Figure 6 shows the x- and z-dependences of the differential polarization, where values of (dP/ds) are averaged over z=0 through 200 pc and over x=0 through 1000 pc, respectively.

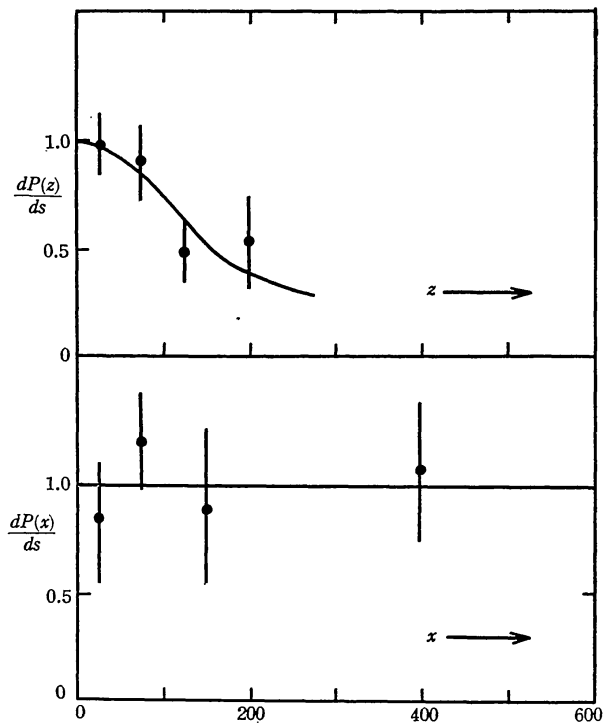

Fig. 6. Distribution of differential polarization in the z- and x-directions in the NPS region. Values in the upper diagram are averaged over x=0 to 1000 pc, and those in the lower diagram are over z=0 to 200 pc. The correlation length of the field in the NPS region is 200 pc in the z-direction and 500 pc or more on the galactic plane.

From these figures we conclude that a region with roughly uniform polarization and, therefore, with uniform magnetic fields and dust distribution extends in the direction $l\approx30°$ at least up to x=500 pc and z=200 pc from the sun. The field line is parallel to the NPS ridge, not parallel to the galactic plane.

If this field structure is due to an SNR, the SNR hypothesis encounters a difficulty in understanding the NPS: a supernova explosion cannot compress the interstellar gas and magnetic fields over such a large area with a scale of 500 pc or more. If, on the other hand, the diffuse radio source of the NPS is generated by the inflation of magnetic fields and cosmic rays out of the interarm bridge (l=30°), this field structure can be understood without difficulty, and it favors the GS hypothesis.

7. *Structure and Distribution of Galactic Spurs*

(i) *Configuration of Spurs Connected with the Galactic Plane*

Radio brightness has been observed to decrease with galactic latitude along most of the spur ridges. If the spurs are due to old SNRs with radii of $\sim$100 pc, such an intensity distribution will be understood as a result of locally different strengths of interaction between the ambient gas and the expanding shells of the SNRs [section 2(ii) d]. Since a radius as large as 100 pc is comparable with the vertical scalelength of the galactic gas layer, the interaction at higher galactic latitudes would be much weaker than that at lower latitudes.

This interpretation seems, however, inconsistent with the assertion that the spur ridge forms a small circle on the sky, although some parts of it are missing. The shock front could not remain spherical during the propagation through the gas layer with magnetic field and density gradient but would be strongly deformed from its spherical structure (see also KAFATOS and MORRISON 1973). It is worthwhile to note radio-brightness distributions of 35 SNRs given by MILNE (1970). Strong deformations from a circular shell are observed in most of them far before their radii reach the vertical scale of the gas layer.

In addition to the well-known spurs said to fall on small circles (Loops I, II, and III), many other spurs emerge from the galactic plane. As summarized in Paper I, we know their good positional correlations with some H I-spurs, MILLS' (1959) steps of background radio continuum, the tangential directions to the spiral arm of the Galaxy, and with the optically dark regions in the Milky Way. These spurs could not be accounted for by SNRs, and no circle has been found to fit them. These spurs, forming Loops I, II, and III, seem to be connected with the complex structure of the galactic plane. In particular, it should be noticed that two prominent spurs emerge vertically from the Cygnus complex region ($l=80°$) into the northern and southern galactic hemispheres (see, for example, the map at 820 MHz due to BERKHUIJSEN [1972]); one is said to be a part of Loop III, while the other is not mentioned by any author from the standpoint of the SNR hypothesis. The GS hypothesis seems more plausible for explaining these circumstances.

Only Loop IV fits a small circle for about 180°, though a large part for another 180° is missing (BERKHUIJSEN 1971; SPOELSTRA 1973). This loop does not come down to $b=0°$. The GS hypothesis cannot explain it. The Origem Loop was found by BERKHUIJSEN (1973a). Its diameter is $4\overset{\circ}{.}6$. This loop may be an SNR shell, and we cannot explain such a small loop by the GS hypothesis.

(ii) *Location of H I and Radio Continuum at the NPS*

An H I-spur is associated in position with the NPS, lying on its convex side about 5° apart from the ridge (BERKHUIJSEN et al. 1971). If the NPS is due to a shock wave of an SNR, the compressed shell of hydrogen gas and of magnetic fields propagates, emitting the λ21-cm line and nonthermal radio continuum. The H I-spur and the NPS must spatially coincide.

If the behavior of interstellar gas along the galactic shock wave is taken into account, the GS hypothesis can explain why the H I-spur is observed on the convex side of the NPS (TOSA 1973b). As shown schematically in figure 7, the interstellar gas is composed of gas clouds with density ρ_c and intercloud gas with ρ_i. The intercloud gas with cosmic ray electrons and magnetic fields is decelerated rapidly and compressed across the shock front at the interarm bridge ($l=30°$), and nonthermal radiation is enhanced here. This enhanced radio emission is observed as

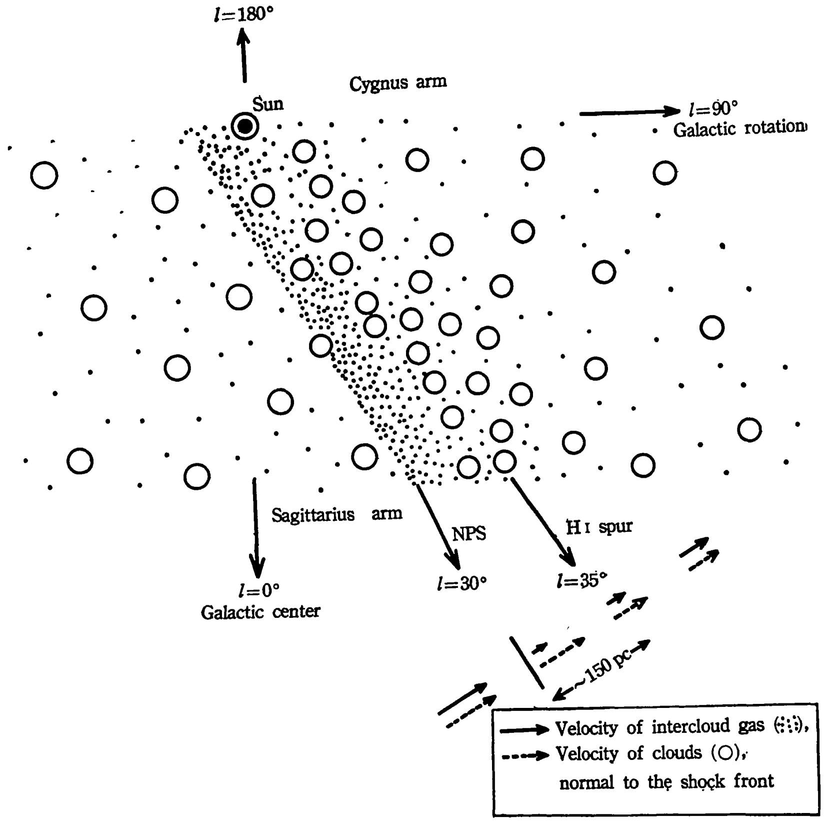

Fig. 7. A schematic structure of the galactic shock wave at the interarm bridge $l=30°$ (TOSA 1973b). Interstellar gas is composed of clouds and intercloud gas. The latter is compressed across the shock front from which enhanced nonthermal radiation is emitted, whereas the clouds accumulate 150 pc behind the shock front. An H I-spur is observed to be shifted to higher longitudes by 5° or so from the NPS.

the NPS of radio continuum. On the other hand, the gas clouds are still moving without deceleration in the shock region, because the mean free path of cloud-cloud collision is 100 pc or more. Drag on the clouds due to the intercloud gas is not effected until the former move through the latter by Δ, where $\Delta \approx (\rho_c/\rho_i) l_c$, and l_c is a typical scale of the cloud. For $\rho_i \approx 0.3\,\mathrm{H\,cm^{-3}}$, $\rho_c \approx 10\,\mathrm{H\,cm^{-3}}$, and $l_c \approx 5\,\mathrm{pc}$, we have $\Delta \approx 150\,\mathrm{pc}$. The cloud velocity begins to drop and the velocity difference between the clouds and intercloud gas vanishes at 130 pc ($=\Delta \cos 30°$) behind the shock front. Consequently hydrogen gas clouds accumulate here and an H I-spur will be observed at increasing longitudes, effectively 5° or so apart from the NPS of radio continuum (figure 7).

8. *Conclusions*

We have examined in some detail the SNR hypothesis for the galactic radio spurs which fall on small circles, i.e., the galactic loops from various data and view points. We summarize our discussions in table 1, where the symbols ○ and ● indicate observational data not inconsistent and inconsistent with these two hypotheses, respectively. Observations with the symbols "—" cannot make definite

Table 1. Summary.

Observations	Hypotheses: SNR (r=10–30 pc)	Hypotheses: SNR (100–150 pc)	Hypotheses: SSNR (100–150 pc)	Hypotheses: GS	Notes
Galactic spurs along small circles	—[1]	●[2]	●[2]	—	(1) Most of the 35 SNRs in MILNE's (1970) data are deformed from perfect circle. Linear diameters of these objects are smaller than 40 pc. (2) When $r>100$ pc, the supernova shell must be deformed.
Galactic spurs not along small circles	●	●	●	○	
Small loops (Origem Loop and Loop IV)	○	○	○	●	
Probability	●	—[3]	—[3]	○	(3) No data for statistics.
Dark regions	●	●	●	○	The optically dark region at l=20–30°, $b>0°$ is considered to be physically associated with NPS.
Hα emission	●[4]	○	○	●	The Hα nebulosities observed near Loops I, II, and III are assumed to be physically associated with these spurs. (4) The upper value of Hα emission at NPS is too small as compared with the Cygnus Loop.
Soft X-rays: NPS	○[5]	○[5]	○[5]	●	(5) It must be remembered that the soft X-rays observed by BUNNER et al. (1972) do not coincide in position with NPS and high expansion velocity is not observed in the H I-spur at l=35° to 40°.
Soft X-rays: Loops II to IV	—	—	—	○	No X-ray enhancement is observed at Loops II–IV.

Table 1. (Continued)

Observations	Hypotheses				Notes
	SNR (r=10–30 pc)	SNR (100–150 pc)	SSNR (100–150 pc)	GS	
Optical polarization in the NPS region	●	●	●	○	
Radial velocities of hydrogen gas at the H I-spurs	●	—	—	○	
Parallel but separate location of the H I-spur and the NPS at $l=30°$ to $35°$, $b>0°$	●	●	●	○(6)	(6) The different behavior between interstellar gas cloud and intercloud gas is taken into account in the galactic shock wave.
Theoretical background	Present	No(7)	No	Present	(7) No supernova remnant with $r>100$ pc has been observed.

contribution to the present conclusions.

Some difficulties seem to exist in the interpretation of the spurs as supernova remnants with radii of 10 to 30 pc or 100 to 150 pc. The hypothesis that the spurs are due to an SSNR with radius of 100 to 150 pc also encounters the same difficulties as the SNR hypothesis, and it has no theoretical background. The GS hypothesis in Paper I is, on the other hand, based on the galactic shock wave at the spiral arm and on the subsequent springing-up magnetic fields out of the spiral arm. In the material so far examined, we prefer the GS hypothesis to the SNR hypothesis, in order to understand the observed data on galactic spurs.

The authors wish to express their thanks to Dr. M. Tosa for his discussions in the course of this work. They also thank Dr. E. M. Berkhuijsen for her critical reading of this paper and many invaluable suggestions and comments.

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