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Loop I (the North Polar Spur)—A major feature of the local interstellar environment

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Abstract. This review concerns itself with Loop I (the North Polar Spur), an angularly immense feature of the high latitude galactic continuum radio emission. Observations of relevance are presented ranging in wavelength from the radio region to γ-rays. The many theories for the origin of the feature are considered. Special attention is paid to the hypothesis that the object is a supernova remnant, at its closest less than 100pc from the sun. The possibility that Loop I may have a major influence on our local interstellar medium is mentioned.

Key words : Galactic loops—H I shells—supernova remnants—local interstellar medium

Introduction

In the ten years since publication of the last general review on the Galactic radio loops (Haslam *et al.* 1971) a wealth of new information has become available. Observations have now been made within most of the possible wavelength ranges. Although our understanding of these intriguing objects still contains a considerable number of loose ends and question marks, the supernova theory of their origin has acquired an enhanced respectability over this period, in large part thanks to the extensive observations of x-ray emission from Loop I.

Four major loops are generally recognized (figure 1) and these are clearly seen in an all-sky radio continuum picture, such as that of figure 2. In addition, a number of further radio loop structures have been proposed (*e.g.* Milogradov-Turin 1970), while the recent discovery of analogous H I and x-ray loop features (*e.g.* Heiles 1979; Nousek *et al.* 1981) suggests that large shells may be a rather common and important feature of the interstellar medium. Such observations would seem to have particular relevance at the present time in view of suggestions that old supernova remnants (SNRs) probably shape the character of a major fraction of the interstellar medium (McKee & Ostriker 1977). Further, it has been proposed that the shells of these old SNRs could be responsible for most of the emission making up the Galactic synchrotron radio background (Berkhuijsen 1971; Sarkar 1982).

For the present review, it has been decided to restrict the material to a consideration of just Loop I. This is the hypothetical structure which includes the bright radio continuum feature often called the North Polar Spur (NPS). The NPS is clearly seen in figure 2 as a bright emission arc, rising roughly perpendicularly from the Galactic plane at $l \approx 30°$, and curving towards lower longitudes to pass only a few degrees from the north Galactic pole. The choice of restricting the material to a consideration of Loop I has been made as a majority of the more recent observations relevant to the Galactic loops deal exclusively with Loop I, which is angularly the largest and the brightest of these objects. While it cannot be automatically assumed that all known loop structures, or even the radio continuum loops, have a similar origin, this would seem a possible situation and an in-depth study of Loop I may well prove to be a fruitful starting point from which to consider the other loops. An additional reason to single out Loop I is the recent proposal that the properties of the local interstellar medium surrounding the sun may well be conditioned by the passage of the outer shock wave associated with the Loop I SNR (Frisch 1981; Crutcher 1982). If this is indeed shown to be the case, this intimate relationship between the object and ourselves justifies special attention being paid to it.

In practice, Loop IV will also receive more attention here than the other loops as it is totally contained within the boundary of Loop I. An association of Loop IV with Loop I has been suggested by a number of authors and its consideration is essential to an understanding of some recent scenarios for the larger, more conspicuous feature.

The basic observational data on Loop I will be presented in sections 2–6 with a minimum of reference to their possible interpretation. This interpretation will be the subject of the subsequent sections.

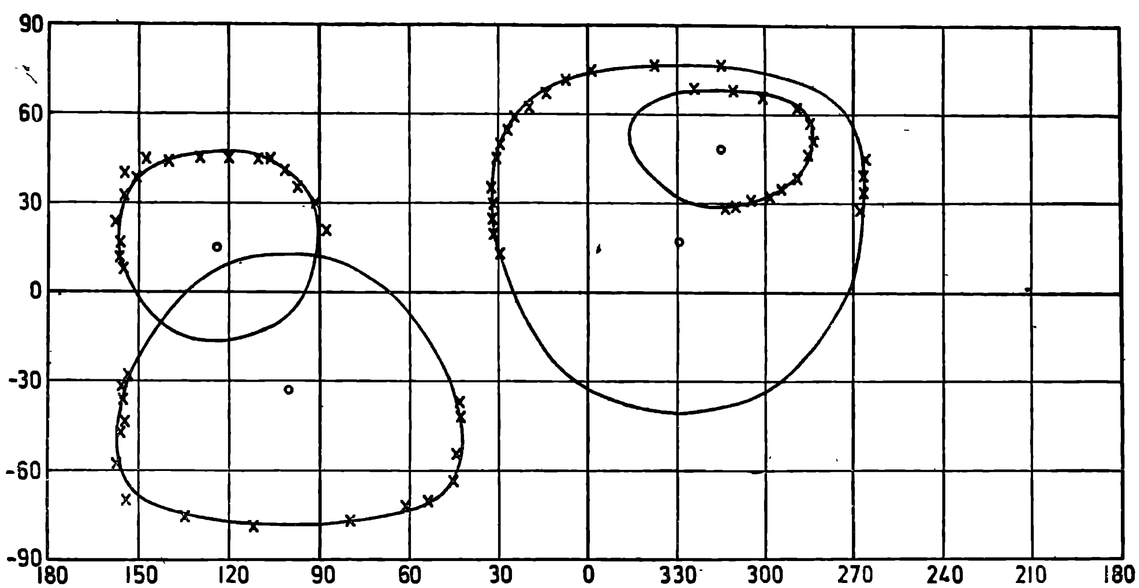

Figure. 1. The small circle geometry of the Galactic loops. The crosses mark the measured ridge positions used to compute the small circles. (Berkhuijsen *et al.* 1971).

2. Radio continuum observations

The NPS is seen as the most prominent feature of the high latitude distribution of radio continuum emission. This radio continuum spur (RCNPS) has been mapped by large area surveys at many frequencies between 2.2 and 1420 MHz and shown by its nonthermal spectrum to be radiating by the synchrotron process. This conclusion is well confirmed by the extremely high precentages of linear polarization found for the radiation at the higher frequencies. As observations of the total intensity and linear polar zation of the continuum emission provide us with information on essentially different physical characteristics of the source we will deal with them separately.

2.1 Total intensity

Although the bright arc of the RCNPS was such an intense feature on early continuum surveys, where, and if, any extension of the arc was to be found was not at all clear. A number of authors (Large *et al.* 1962; Davies 1964; Guidice 1971) connected the feature with the fainter emission arc near (300°, 65°)*, now usually considered to be part of Loop IV. However, using a stereographic projection, Large *et al.* (1966) noted that the RCNPS followed a small circle in the sky to excellent approximation. They demonstrated that a weak continuum ridge, lying along $l \approx 268°$ and of some 25° length, fitted well with the predicted path of this small circle, despite some divergence from the circle below $b = 25°$. Although any emission linking the two ridges is below the sensitivities of existing surveys and the proposed connection is purely geometrical, their association has been widely accepted. The hypothetical circular object in the sky, of which these ridges form the observable radio segments, has become known as Loop I. It should be stressed that the exact geometry, and even reality, of such a feature is not a complete certainty. In particular, evidence for the continuation of Loop I below the Galactic plane is at best fragmentary. On the other hand, observations described below of the λ 21cm neutral hydrogen line, and of soft x-rays, strongly support the NPS being part of a larger coherent structure. Berkhuijsen *et al.* (1971) fitted a small circle to the radio ridge peaks and derived a centre for the Loop I feature of (329°.0 ± 1°.5, 17°.5 ± 3°.0) and a diameter of 116° ± 4°. Over the 155° arc of the circle where data was measurable, the r.m.s. deviation of the observed ridge from the fitted circle was 0°.9.

The ridge through (300°, 65°), originally considered to be the extension of the RCNPS, was shown by Large *et al.* (1966) to form part of a semicircular feature in its own right. Berkhuijsen *et al.* (1971) named this Loop IV. The large, semicircular features, Loop II (The Cetus Arc) and Loop III, are also discussed by Berkhuijsen *et al.* These authors fitted a small circle to Loop IV but from a recent 1420 MHz survey of part of this loop, Reich & Steffen (1981) suggested that the continuum ridge deviated significantly from the Berkhuijsen *et al.* fit. The present author has refitted the circular geometry of Loop IV using the recent 408 MHz maps of Haslam *et al.* (1982). He finds a centre of (315°.75 ±3°.0, 48°.25 ± 1°.0) with a diameter of 39°.75 ± 2°.0 and an r.m.s. deviation of only 0°.6. This solution is within the quoted errors of the earlier work.

*Galactic coordinates will be given as coordinate pairs enclosed in brackets.

Apart from Loop IV, Large *et al.* (1966) catalogued a number of other continuum ridges within Loop I. These were confirmed and added to by a number of authors (Merkelijn & Davis 1967; Holden 1969; Berkhuijsen 1971; Haslam *et al.* 1981). Large *et al.* found that, with the notable exception of Loop IV, most of the ridges were roughly concentric with Loop I. Berkhuijsen (1971) came to a similar general conclusion but noted that a few ridges in her extensive collection of these features deviated markedly from the rule. She also pointed out that a number of ridges apparently associated with Loop I, including some side branches of the main RCNPS ridge, were situated outside the small circle defining the loop. This observation, together with the linear polarization studies of the same author and the H I observations (see sections 2.2 and 3), indicates that the zone of influence of Loop I is even more extensive than suggested by the RCNPS. Holden (1969) had already concluded that emission outside the main ridge of the RCNPS at lower latitudes appeared to be an extension of the object. Observing at 178 MHz with the relatively high resolution of 20 arcmin, Holden detected abrupt *steps* in the edge gradients of both the RCNPS and the internal and external ridges. Across a typical step, the brightness temperature increased abruptly by some 100 K. Despite their small angular width, being often unresolved to the 178 MHz beam, the steps had typical lengths of 6°. For a distance to such a step of 100pc, the linear projected size across the step would be $\lesssim$ 0.4pc, whereas its projected length would be $\approx$ 12pc.

The main ridge of the RCNPS possesses a number of distinctive features. Davies (1964) showed that its outer edge has a considerably steeper gradient than the inner edge and further suggested that the brightness temperatures within the loop are higher than those outside. He concluded that both these results are consistent with the physical object giving rise to Loop I having a shell structure. On this assumption he computed that such a shell would have a thickness of about 7–11% of the radius. Guidice (1971) derived a typical radial profile across the RCNPS (figure 3) which agreed with both the suggestions of Davies. He fitted a shell with a thickness of 13.5% of its radius to the profile, noting that this thickness was probably overestimated by 15–25% owing to beam broading. Haslam *et al.* (1964) discovered an intriguing feature of the RCNPS from their 240 MHz observations at lower latitudes. The main ridge of the Spur appeared to display a *narrow neck* at $11° \leqslant b \leqslant 16°$ with the width of the ridge increasing above these latitudes. Although Holden (1969) concluded that the NPS did not extend below $b \approx 11°$, Berkhuijsen *et al.* (1971) traced the main ridge to below $b \approx 8°$ and could follow the bright inner ridge passing through (22°, 14°) to $b \approx 4°$. Recently, Sofue & Reich (1979) published 1420 MHz maps of the RCNPS at low latitudes having the highest resolution (H.P.B.W. = 10 arcmin) yet available for the object. These authors believe they can follow the RCNPS from (33°, 20°) right down to (22°, 3°). For the *narrow neck* they find a typical width of 0°.8, with no evidence for a particular narrowing of the ridge in the neck, although the ridge does split into several subridges for $b \geqslant 11°$. They do, however, find the ridge to be narrower at the lowest latitudes and the *narrowest width* of the RCNPS seems to increase quasilinearly with latitude over the entire range $3° \leqslant b \leqslant 20°$. The narrow, low latitude extension between (24°, 6°) and (22°, 3°) seems to be a genuine extension

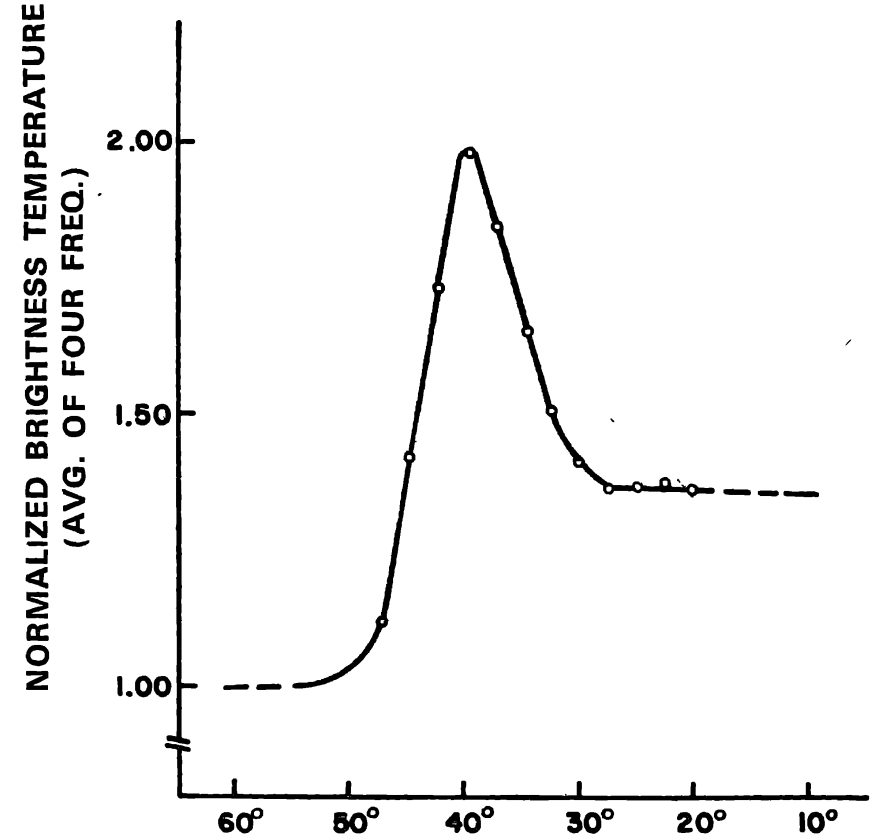

Figure 3. An experimentally determined, radial, radio continuum profile of NPS through the position RA = 14^h, dec = 20°. Note that RA = 15^h10^m, dec = −17°, (345°, 34°) was taken as the Loop I centre in the preparation of the profile. (Guidice 1971).

of the main ridge, with a width of about 0°.3. No further extension into the plane or at southern latitudes is found.

Since the days of the earliest surveys there has been little doubt that the RCNPS radiates predominatly by the sychrotron mechanism. This is demonstrated both by its steep radio spectrum above 100 MHz and the high percentage polarization found for the emission above 400 MHz. Neverthless, the exact form of the radio continuum spectrum is still not well defined, with the possibility existing of a flattening, or even turnover, in the low frequency spectrum. In addition, it has sometimes been suggested that the spectral properties of the object may be partly shaped by the presence of ionized material either within the object or in the foreground.

At decimetre wavelengths, the most detailed study of the NPS spectrum has been made by Berkhuijsen (1971) who used the technique of T—T plots to derive spectral indices ($S \propto \nu^{-\alpha}$) between 240 and 820 MHz. The values of α she obtained had typical absolute errors of 0.25, although the random internal errors were much smaller. For the latitude range $17° < b < 43°$, Berkhuijsen found $0.55 < \alpha < 0.72$, with the lowest values at the lowest latitudes. She noted that a similar trend was present in the spectral index maps made between 85 and 150 MHz by Landecker (1969). From her $T-T$ plots Berkhuijsen concluded that (i) for constant brightness temperatures at 240 MHz, the 820 MHz temperatures inside the main ridge of the NPS were higher than those outside; (ii) the slope of the $T-T$ plots was the same inside and outside the NPS; (iii) the temperature difference between the $T-T$ segments inside and outside the NPS was ≈ 0.4K at 820 MHz; and (iv) the temperature increase set in over the inner gradient of the NPS near $l = 20°$, having its maximum value on top of the inner ridges. To explain these effects she proposed the presence of a smooth, low spectral index component between $20° \lesssim l \lesssim 30°$ over the entire latitude range considered. She believed that this component consisted of ionized hydrogen with an average emission measure of about 70 cm^{-6} pc, and a maximum emission measure of 170 cm^{-6} pc at $b = 27°$ where a low value of α was found.

At low frequencies the situation is rather less clear, with the early studies often producing mutually contradictory results. Davies (1964) obtained $\alpha = 0.55 \pm 0.08$ between 38 and 178 MHz. Bridle (1967) suggested that the NPS had a lower spectral index between 17.5 and 81.5 MHz than the surrounding regions, and computed $\alpha = 0.1 \pm 0.2$. Baldwin (1967) reported that the Penticton 10 MHz observations of Purton showed absorption patches along the NPS ridge and Berkhuijsen (1971) identified these with her proposed H II component described above. More recent measurements seem to clarify the situation somewhat, and very low values of spectral index at decametric wavelengths now seem less likely. First, Guidice (1971) concluded from four frequency observations that the spectral index between 20 and 40 MHz is $\alpha = 0.5 \pm 0.15$. Caswell (1976) produced an updated Penticton 10 MHz map of the northern sky which included the section of the NPS earlier than right ascension $15^h 30^m$. No absorption patches are apparent and the author concludes that from 10 MHz to 38 or 178 MHz the spectrum of the RCNPS is at least as steep as, perhaps steeper than, the surrounding Galactic emission. He points out that Bridle obtained his value of α after subtraction of a *steeper than average* underlying background. Finally, Novaco & Brown (1978) claim that the RCNPS can be seen in emission on their low resolution observations made between 2.2 and 9.2 MHz. They find that at 1.3 MHz the feature is no longer visible and this they attribute to absorption in the intervening interstellar medium.

Spectral information concerning Loop IV is scarce, though Reich & Steffen (1981) note that Loop IV has a nonthermal spectrum.

2.2 Linear polarization

Linear polarization of the radio emission from the RCNPS can be clearly seen from observations covering the frequency range 408–1415 MHz. Typical of these studies are the extensive series of observations made during the 1960s using the 25m Dwingeloo telescope at a number of frequencies and recently produced as an atlas of maps by Brouw & Spoelstra (1976). The 1415 MHz map from this compendium is shown in figure 4 and demonstrates the high polarization over the NPS.

A noteworthy early study of polarization data was made by Bingham (1967) who combined his own 1407 MHz data, covering virtually the whole RCNPS, with already existing lower frequency Dutch results. Subsequently, the full Dutch observations were interpreted in a series of papers (Berkhuijsen 1971; Spoelstra 1971, 1972).

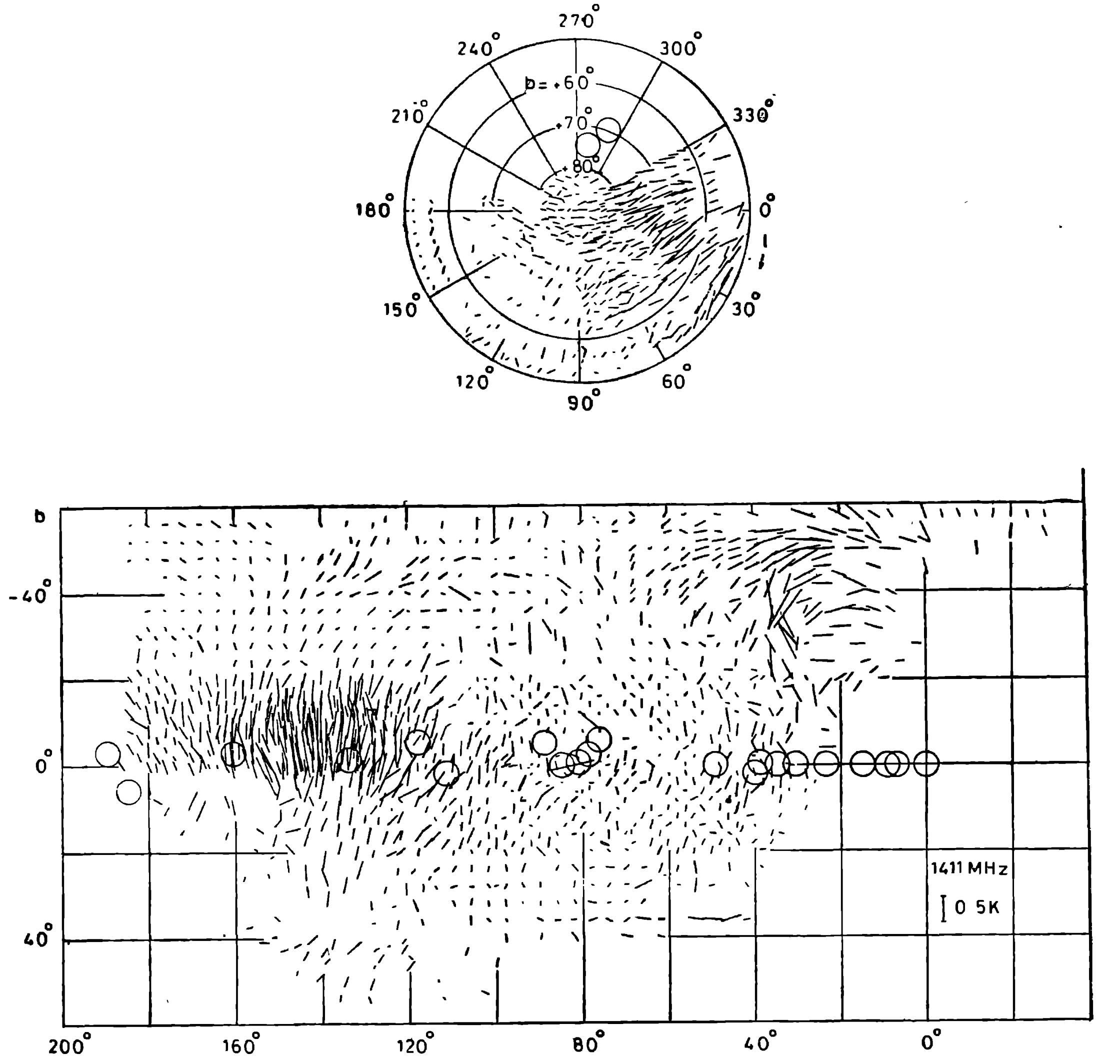

Figure 4. Distribution of linear polarization at 1411 MHz. The length of the *polarization vectors* are proportional to the intensity of the polarized radiation, whereas the direction of the vectors gives the polarization angle (*i.e.* direction of the electric field component). The circles indicate the presence of point sources which may have influenced the results. (Brouw & Spoelstra 1976).

Bingham presented a map of rotation measure (RM) over the NPS for $b \geqslant 40°$. He found that the sign of RM was mostly positive with its magnitude increasing towards lower latitudes. Towards the north Galactic pole, the RMs were very small and alternated in sign suggesting that the magnetic field traversed by the radiation was essentially perpendicular to the line of sight (*i.e.* parallel to the Galactic plane). He took the existence of extensive polarization on the 408 MHz Dutch maps to mean that most of the rotation is occurring between the NPS and the sun, rather than within the source which would give large front-back depolarization at this frequency. Spoelstra presented RM maps separately for the low and high latitude sections of the NPS in his two publications. At $b > 50°$ his derived values of RM are rather higher than those of Bingham, with an average value of ≈ 4 rad m^{-2}. Below $b = 50°$ the rotation measures are generally $\leqslant 14$ rad m^{-2}, the higher values being found where the projected magnetic field direction becomes perpendicular to the NPS (see below). Spoelstra concluded that for generally accepted values of the interstellar magnetic field of 1–5μG and an electron density of 0.06 cm^{-3}, the RMs are consistent with a distance of 50–100pc. This strongly suggests that the NPS is a relatively local object.

Using the values of RM to derive intrinsic polarization vector directions, Bingham found that above $b \approx 40°$ the magnetic field in the emission regions is essentially parallel to the NPS for at least 15° on either side of the ridge peak. For high latitudes Spoelstra arrived at a similar conculsion, but below $b \approx 45°$ he revealed a very different situation. Within an area $30° \leqslant l \leqslant 35°$, $26° \leqslant b \leqslant 40°$ the intrinsic polarization position angles imply a magnetic field that is essentially perpendicular to the NPS. This is also so for positions on the internal ridges running through (24°, 27°) and (24°, 35°). Perhaps significantly, this area of the RCNPS is where the radio continuum structure appears to show a superposed semicircular feature on, and inside, the main ridge (Haslam, Salter & Sieber, personal communication). This circular structure (figure 5) can be followed over

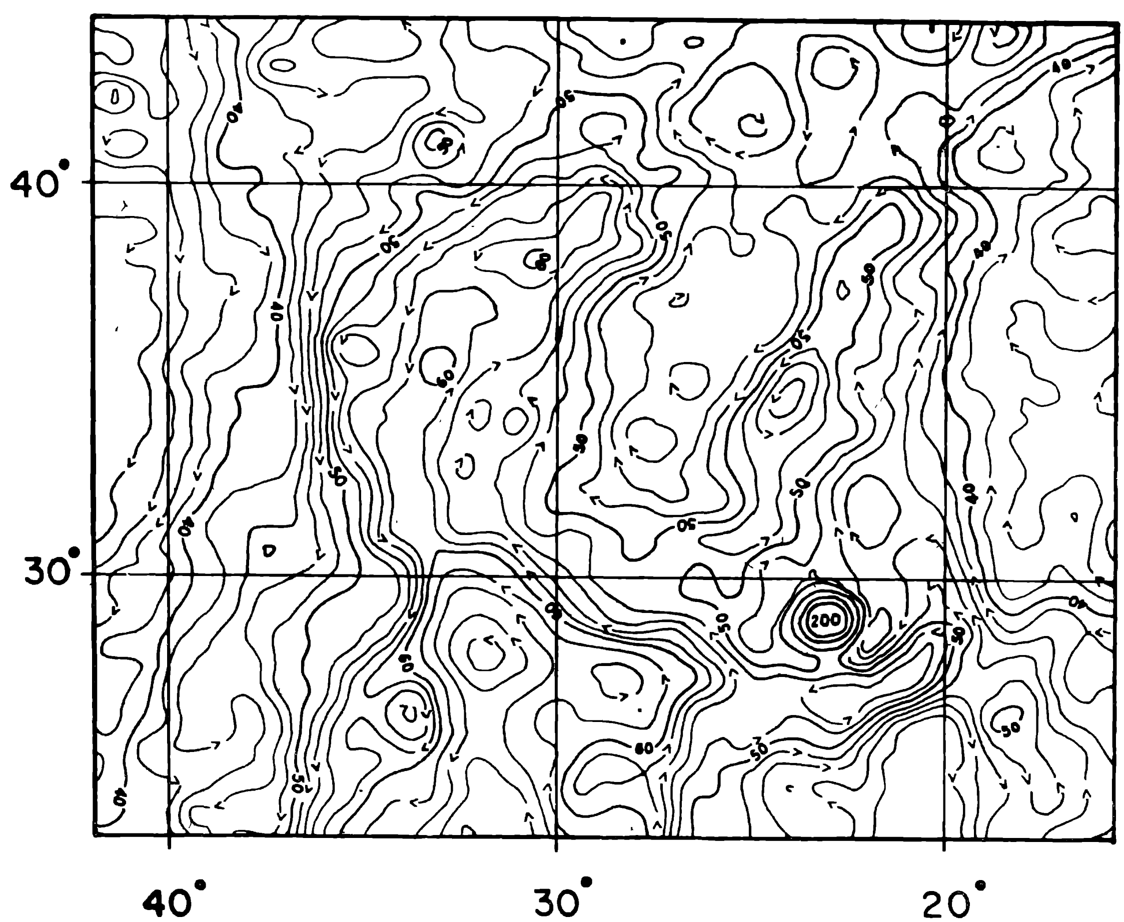

Figure 5. The semicircular radio continuum feature superposed on the main ridge of the NPS. The contours are from the 408 MHz all-sky survey of Haslam *et al.* (1982) and are labelled in K. Arrows on contour lines point clockwise around minima in the brightness distribution and anticlockwise around maxima. (Haslam, Salter & Sieber, personal communication).

200° of a circle centred on (25°.8 ± 0°.6, 33°.3 ± 0°.6) and of diameter 13°.5 ± 0.8. Its ridge peak deviates from this best-fit small circle by some 0°.35. Spoelstra showed that above $b = 45°$ the polarization vectors swing round from parallel to perpendicular to the NPS ridge. This effect sets in at lower latitudes just outside the spur ridge.

To estimate the percentage polarization of the RCNPS emission Bingham plotted his polarization temperatures T_B^P against the total power temperatures T_B at each point. At high latitudes, where the RM's are small, he found a strong correlation between the two quantities. The slope of the best-fit straight line to the plot suggested a uniform degree of polarization on the RCNPS of some 50–60% when observed with a resolution of 2°. Such a high value implies that the magnetic field within the object is well aligned in depth. Berkhuijsen also investigated the percentage polarization of the RCNPS radiation using plots of T_B^P against T_B at a given latitude. From these plots she arrived at the following conclusions :

(i) Below $b \approx 30°$ no relationship existed between T_B^P and T_B.

(ii) For $b > 30°$ straight lines fitted the plots well, giving a polarization percentage that increased with increasing latitude.

(iii) For $50° < b < 70°$ the polarization percentage at 1411 MHz was about 74%, roughly the maximum possible value for synchrotron emission. She believed that the somewhat lower values found by Bingham were caused by depolarization due to the larger beamwidth of the Cambridge observations.

(iv) The polarization percentage at 820 MHz was invariably lower than at 1411 MHz. This she ascribed to a combination of the depolarizing effect of the greater Faraday rotation, and the larger telescope beamwidth, at the lower frequency.

(v) She believed the polarization percentages to be somewhat lower on the RCNPS ridge peak which she noted would be consistent with Faraday depolarization in the H II layer she had proposed to be present there (see section 2.1).

(vi) From the T_B values at the $T_B^P = 0$ intercept of the best-fit straight lines, she concluded that an essentially unpolarized background of rather uniform intensity underlies the RCNPS emission at all latitudes considered.

Using a similar technique, Spoelstra confirmed that the polarization percentages were close to the theoretical maximum for $65° \leqslant b \leqslant 75°$, demonstrating again the extreme regularity of the field. Below $b = 50°$ he still found regions with polarization percentages greater than, or equal to, 75% of the theoretical maximum. He noted that the highest percentages there are found at $b = 35°$ and $b = 50°$. He estimated that in these regions of the NPS the ratio of the strength of the ordered magnetic field component perpendicular to the line of sight to that of the random field component is about 2.8. However, he agreed with Berkhuijsen that near the $b = 20°$ lower latitude limit of his survey, there is no linear polarization markedly greater than that of the general Galactic background. Interestingly, at no point did Spoelstra find any positional shift between the maximum of the total power and polarized intensities.

In the latitude range $40° < b < 55°$, Bekhuijsen found that the high polarized intensities at 1411 MHz continued far outside the RCNPS to about $l = 60°$. From the position angles of the polarization vectors she suggested that this effect was related to Loop I. This, together with the existence of total power ridges and steps outside the RCNPS (see section 2.1), led her to conclude that the influence of Loop I can be seen considerably beyond the main ridge of the RCNPS. Spoelstra pointed out that the radiation from the ridges inside Loop I is highly polarized. Where ridges meet he found lower polarization percentages, presumably due to the vector-summing of components of different position angle within his beam. Spoelstra could not detect any direct continuation of the NPS beyond $l \approx 320°$ in the polarized intensity distribution. Finally, in no part of the NPS could he find any correlation between either the polarized intensity or RM distributions and that of the surface density of neutral hydrogen (see section 3).

Spoelstra (1973) noted that at 1415 MHz no polarization was evident for the continuum emission from the section of Loop IV above $b \approx 50°$. This could be taken to imply that Loop IV is farther from the sun than the NPS and hence suffers greater interstellar depolarization.

2.3 Evidence from small diameter sources

Small diameter radio sources have been used in a number of attempts to cast light on features of the NPS. The first suggested correlation came when Edge *et al.* (1959) reported an excess of sources of flux density > 8 Jy at 159 MHz in the region of the NPS. Foster (1961) derived a similar result for sources above 6 Jy at 178 MHz. Holden (1969), however, examined the distribution of source down to 2 Jy at 178 MHz and found no significant excess. The same conclusion was reached by Sofue & Reich (1979) for the distribution of sources on the NPS down to 0.25 Jy at 1420 MHz. It seems that the existence of a statistically significant excess of small diameter sources connected with the NPS is not tenable on the present evidence.

An interesting possibility was raised by Shapirovskaya (1978) who noticed that the fifteen then-known, low frequency, variable radio sources all lie in the directions of continuum loops, spurs or ridges. She believed this to be statistically significant and derived a scale size of 10^{13} cm for irregularities in the loops which she postulated to be causing the variability through scintillation. However, Fanti *et al.* (1982) have since pointed out that her conclusions on the sky distribution of low frequency variables are no longer supported by the distribution of the present increased number of known, or suspected, variables.

A somewhat different effect has been suggested by Rickard & Cronyn (1979). These authors reexamined the Cambridge 81.5 MHz interplanetary scintillation results, dividing the sky into boxes of about $15° \times 15°$ and comparing the number of nonscintillators in each box with that expected. Away from the Galactic plane only three boxes possessed an excess of nonscintillators at the $> 2\sigma$ level. These three boxes were contiguous, stretching from $b = 10°$ to $65°$ at $l \approx 60°$. The probability that the only three boxes should be contiguous by chance is put at $\approx 0.05\%$ The authors note that the line of boxes is parallel to the NPS and suggest that the lack of scintillators could be due to scattering in an *outer turbulence shell* of the NPS. As the longitude of such a feature would be some 90° away from the centre of Loop I, the sun should be located close to, if not actually inside, the turbulence shell itself.

The distribution of rotation measures (RM) of polarized extragalactic radio sources is believed to show the influence of Loop I. Gardner *et al.* (1969) and Vallée & Kronberg (1975) invoked the NPS to explain the anomolous zone of RM north of the Galactic plane. This effect is highlighted by Simard-Normandin & Kronberg (1980) who point out that whereas the RMs at negative latitudes are mostly negative for $0° < l < 180°$ and positive for $180° < l < 360°$, at positive latitudes they are positive for $0° < l < 90°$, with the sign alternating in successive quadrants. To explain this they propose that Loop I is perturbing the local magnetic field at positive latitudes in the first and fourth quadrants. Inoue & Tabara (1982) also find the same anomolous zone of positive RM near $l = 40°$ for $30° \leqslant b \leqslant 60°$ and similarly conclude that it is due to the NPS.

3. Radio observations of neutral hydrogen

The first mention of a correlation between the distribution of H I derived from observations of the $\lambda 21$ cm radio spectral line and Loop I was due to Lozinsakaya (1964). She noted that there appeared to be a deficiency of H I on the main ridge of the RCNPS when compared with surrounding regions. The situation was clarified by Berkhuijsen *et al.* (1970, 1971). They demonstrated that the steep outer gradient of the RCNPS coincides with an H I spur on the maps of McGee *et al.* (1963). This spur will be referred to below as the H I NPS. Berkhuijsen *et al.*, also noticed a close coincidence between shorter H I ridges and the outer gradients and peaks of a number of Loop I continuum ridges. They used the unpublished H I maps of van Kuilenberg to confirm the existence of an extensive H I NPS (figure 6). At the lower latitudes most of the H I had positive velocities of $\leqslant +30$ km s^{-1}, although they believed that patches of associated H I were visible between +30 and 50 km s^{-1}. Berkhuijsen *et al.* also examined existing observations covering the high latitude regions and concluded that there also low and intermediate velocity gas seemed to be associated with Loop I. Finally, they pointed out that on the H I survey of Grahl *et al.* (1968) made along $b = 30°$, there was a coincidence between Loop I and two features, narrow-in-longitude with high velocity dispersion, extending to positive velocities.

From the observations of van Kuilenberg, Berkhuijsen *et al.* derived a surface density half width for the H I NPS of 5° and find that, on average, it lies some 5° outside the RCNPS. They gave a mean H I surface density for the feature of $(2.0 \pm 1.0) \times 10^{20}$ cm^{-2}. Assuming that the H I is distributed in a spherical shell of uniform density, they tabulated values for the shell thickness, H I density and mass of the shell as functions of distance.

At about the same epoch Verschuur (1970) used the N.R.A.O. 300 ft telescope to map the H I in a region of sky on the outer gradient of the RCNPS at $b \approx 50°$. He found an extended H I feature elongated parallel to the direction of the NPS. This H I filament possessed small scale spatial and velocity structure. with discrete boundaries less than a beamwidth (10 arcmin) in extent. He noted that the H I peaks at various velocities were positionally anticorrelated. Later, the same author mapped two further areas on the RCNPS outer gradient (Verschuur 1974). These were centred at (27°, 64°) and (42°, 44°). Both contained filamentary structure aligned parallel to the NPS. For one region Verschuur noted that there was a

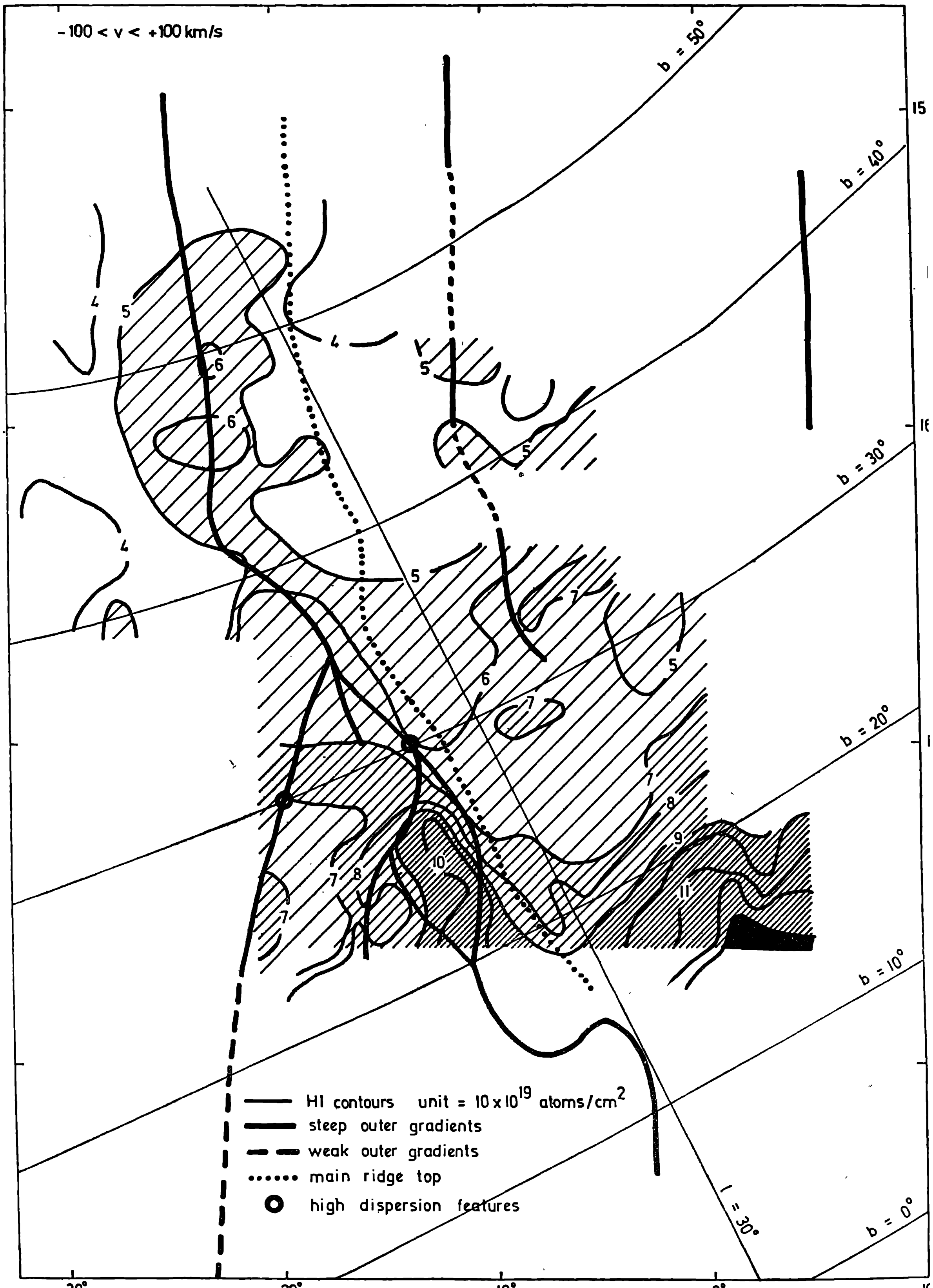

Figure 6. The H I surface density in the region of the NPS for the radial velocity range -100 km s^{-1} to $+100$ km s^{-1}. (van Kuilenberg, reproduced in Berkhuijsen *et al.* 1971).

radial velocity gradient perpendicular to the axis of the NPS, with H I close to the RCNPS being concentrated at positive velocities whereas further away the emission being predominantly at negative velocities. Useful information also came from van Kuilenberg (1972) who mapped the high velocity gas in velocity ranges $60 < | V | < 270$ km s^{-1} at latitudes $| b | \geqslant 15°$. He found no correlation between the high velocity gas and Loop I.

Fejes & Wesselius (1973) presented an analysis of the Groningen high latitude H I survey for $15° < | b | < 80°$. They found a ridge running along $l \approx 35°$ for $b = 25°$ to $70°$ which they named the *Hercules ridge*. This is coincident with the H I NPS. In the brightest section between $b = 25°$ and $55°$ the excess surface density is about 1.5×10^{20} cm^{-2}. On the opposite side of Loop I they found another ridge (named by them the *Sextans ridge*) running from $b = 15°$ to $70°$ at $l = 240°$ to $260°$. While the Hercules ridge lay on the outer gradient of the RCNPS, they noted that the Sextans ridge had an irregular structure and lay 5°–15° outside the continuum ridge near $l = 268°$ which is usually taken to define the Loop I extension beyond the RCNPS. At the highest latitudes they found small elongated H I concentrations aligned parallel to Loop I from $l = 260°$ to $335°$ at $b \approx 80°$. They also drew attention to an H I ridge running from (270°, −10°) to (295°, −30°) that could lie along the Loop I small circle, south of the Galactic plane. No excess continuum emission has yet been found in that region.

Heiles & Jenkins (1976) interpret the fully-sampled H I data available from the Hat Creek λ21 cm survey. Considering the low velocity gas, they find H I features consisting of a number of elongated structures running roughly parallel to the RCNPS. Typical sizes for these structures are $10° \times \leqslant 2°$, and some have large bends rather than following the NPS smoothly. Consistent with previous work, they find this H I NPS to lie outside the RCNPS, with their general association continuing into the polar regions. Above $b = 60°$, however, the H I structures becomes more crooked, longer and thicker, while the separation between the H I and the radio continuum increases to some 15°. The H I then bends back towards the Galactic equator at about $l \approx 250°$, and between $b = 50°$ and 10° the regular extension of the H I NPS vanishes and the H I is seen as many weak, delicate, randomly orientated, interconnecting filaments showing no overall structure. Heiles & Jenkins state that they find no coherent feature representing the Sextans ridge of Fejes & Wesselius and surmise that some physical process may have destroyed the coherence of a larger, more organised extension of the H I NPS. As possible evidence for this they cite the presence of large relative velocities in the gas. Finally, they conclude that the H I of Loop I does not *necessarily* continue to southerly latitudes at the $b = 250°$ end. It is of interest that they find no correlation between the intermediate velocity gas and the NPS.

Cleary *et al.* (1979) extend the work of Heiles & Jenkins to the southern hemisphere using a survey made with the Parkes 60 ft telescope. Their maps show an intense, low velocity filament of H I stretching from (250°, −10°) to (330°, −22°). This they identify with the filament which Fejes & Wesselius suggested could be a southern extension of Loop I, a conclusion which they believe to be possible, despite the absence of radio continuum emission. They suspect that the filament could be weakly correlated with a feature in the distribution of the linearly polarized component of the continuum. From all-sky H I data, Colomb *et al.* (1980) find a quasicircular feature of about 90° angular diameter, centred on (320°, 15°) which they associate with Loop I. This is only seen in the negative velocity gas and its diameter gets smaller for more negative velocities suggesting that the gas is contained in an expanding spherical shell. The feature can be followed right to the negative velocity limit of the survey at -38 km s^{-1}. In the light of this result, Heiles *et al.* (1980) revised their estimate for the expansion velocity of a hypothetical Loop I shell from a very low value, up to some 30 km s^{-1}. Additionally, Heiles *et al.* (1980) report that observations of the H I NPS with a resolution of $\approx$3 ft indicate that there is no small scale structure within the H I.

A particularly interesting piece of work has recently appeared (Troland & Heiles 1982). These authors attempted to measure the strength of the line-of-sight component of the magnetic field within Loop I by means of the Zeeman splitting of the H I profile. They made observations at pairs of positions at (5°, 34°) on an H I filament within Loop I and at (37°, 40°) on the H I NPS. At all positions they set upper limits on the line of sight component of the field of 4–5μG. The similarity of this limit to the general interstellar field strength derived from the rotation measures of local pulsars leads them to conclude that there is probably little field enhancement within the probable Loop I shell. They suggest that the region of anomolous rotation measure on the NPS (see sector 2.3) is associated with an increase of the electron density within the object rather than with an enhancement of the magnetic field.

Attempts to associate H I with Loop IV have left us in a rather confused situation. Fejes (1971a, b) observed the entire area of Loop IV in the λ21 cm line. From his map of the distribution of the maximum intensity of the line, he found a weak spur which lay within 2°.5 of the best-fit small circle to the loop over an arc-length of 180°. The half power velocity width of the gas was 10 ± 3 km s^{-1}. A similar feature is seen in the distribution of surface density of the H I between radial velocities $-6 \leqslant V \leqslant +2$ km s^{-1}. Fejes also believed that the gas towards the interior of the loop showed evidence for expansion and suggested that the whole feature is a shell expanding with a velocity of 30–40 km s^{-1}. Later, Fejes & Wesselius (1973) quoted an average value for the excess H I surface density on the Loop IV ridge of $\approx 0.3 \times 10^{20}$ cm^{-2}. However, more recently the situation has been complicated by Heiles & Jenkins (1976). From an examination of the Hat Creek survey they conclude that there is no filamentary structure with the same shape and position as Loop IV and that they find no convincing association of H I with Loop IV.

4. Optical observations

4.1 Direct detection

To date, attempts to detect optical emission from the NPS and Loop I have not met with spectacular success. Nevertheless, they have established remarkably low limits on the emission measure of material associated with the loop. These limits represent one of the fundamental inputs that must be considered in the interpretatation of the object.

Spurred on by the possibility that the NPS might represent a nearby SNR, Davies *et al.* (1963) took H_α photographs of a number of known SNRs and of three regions on the NPS where intense radio emission with well defined edges was to be found. One region of the NPS was also photographed at 3727 Å in an attempt to detect [O II] emission. They estimated that the surface brightness of the NPS at H_α was $\leqslant$ 0.003 that of the Cygnus Loop SNR, while for [O II] the ratio was $\leqslant$ 0.3. They further deduced that the ratio of H_α to radio continuum surface brightnesses for the NPS was $\leqslant$ 0.002 that of the Cygnus Loop. From these comparisons they concluded that if an SNR the NPS had very different optical properties from the other SNRs they considered. These SNRs (Cygnus Loop, IC443, HB9, S147) are usually believed to be in the adiabatic expansion phase. In two later papers, Meaburn (1965, 1967) extended the previous work. While in no case was he able to detect filamentary nebulosity associated with the NPS, he believed diffuse optical emission to be present, covering the NPS. Whether this emission was connected with the radio continuum features was not clear.

Recently, Heiles *et al.* (1980) have pursued the attempt to detect optical emission from Loop. I. They made $H\alpha$ measurements across the NPS at $b = 42°$ and 45°. Using a Fabry-Perot spectrometer of 45 arcmin resolution, they obtained a sensitivity equal to an emission measure of 2 cm^{-6}pc for gas at 8000 K. They found a possible enhancement of the $H\alpha$ intensity at $l = 32°$–33°, roughly coincident with the radio continuum peak, and concluded that the (absorption corrected) emission measure is $\leqslant$ 10 cm^{-6}pc. The width of the Gaussian fit to this possible detection yielded a temperature of $<$ 9000 K. It should perhaps be noted that the above limit on the emission measure is an order of magnitude lower than that predicted for the H II component suggested by Berkhuijsen (1971) from her radio continuum spectral studies (section 2.1).

4.2 *Optical polarization of starlight*

In his study of the Galactic spurs, Bingham (1967) pointed out that the effects of the NPS could be seen not only in the polarization of the radio continuum but apparently also in the optical polarization of starlight. He found that the optical polarization vectors on the NPS indicate that above $b \approx 40°$ the magnetic field aligning the polarizing dust is essentially parallel to the NPS for at least 15°on each side of the spur ridge. The polarization vectors of all stars considered by Bingham at distances between 90 and 120pc were parallel to the NPS, as were those of two stars at about 75pc. Stars considered at less than 70pc showed little polarization and did not reflect the structure of the spur. He concluded that the distance to the NPS is 100 $\pm$ 20pc, with there being some evidence that this distance decreased towards the centre of curvature of Loop I, consistent with a spherical structure. Since this work of Bingham, distances to the NPS derived from optical polarization have usually been given the greatest credence.

From polarization data for 1400 stars, Mathewson (1968) drew attention to what he believed to be a correlation between the local magnetic field direction and the Galactic loops. He interpreted the directions of the polarization vectors in terms of a helical component of the local field, as will be discussed further in section 7.

He also found that the optical polarization increases rapidly at about 100pc, although he cautions that the magnetic field of the RCNPS is not necessarily the same as that aligning the dust which gives rise to the optical polarization. After dividing the available measurements into a number of distance classes, Seymour (1969) performed a spherical harmonic analysis of the polarization of starlight. He found evidence that a cloud responsible for the polarization of stars nearer than 30pc may have originated in the NPS. Seymour concluded from his full analysis that the main ridge of the NPS lines somewhere between 0 and 110pc.

Spoelstra (1971, 1972) provided evidence that justified Mathewson's cautionary note and disturbed the neat picture of spatial coincidence between the optically polarizing dust grains and the regions of synchrotron emission in the RCNPS. Spoelstra pointed out that if the origins of the radio and optical polarization were spatially coincident then the two sets of intrinsic polarization vectors should be mutually perpendicular. Disconcertingly, he found that while above $b = 40°$ this orthogonality holds, below this latitude the radio vectors swing round (see section 2.2) to become essentially parallel to the optical vectors. Spoelstra also examined the change of optical polarization percentage against distance for stars between $b = 20°$ and 50°. He found no indication that the increase of percentage with distance was any different on the RCNPS to outside the spur. On this evidence he concluded that while the optical polarization vectors are remarkably parallel to the NPS at all latitudes the possibility could not be ruled out that this might be a chance effect. However, he also noted that the optical and radio polarization need not necessarily originate in the same volume of Loop I and conjectured that the absence of additional absorption in the RCNPS might mean that a lower density of grains are present in that region. In fact for the region of the NPS above $b = 60°$ he found the optical percentage polarization to be somewhat higher towards the RCNPS than outside. Spoelstra computed the most likely distances to the top of the NPS to be around 80pc.

Later work by Axon & Ellis (1976) confirms that for stars in the distance range 50 to 100pc, as well as for those beyond, the optical polarization vectors are clearly parallel to the NPS (figure 7). Ellis & Axon (1978), however, noticed that the optical vectors tend to veer away from the path of Loop I near the Galactic plane at $l \approx 30°$ and point towards higher longitudes. The same authors found that the presence of Loop IV was not evident in the optical polarization data. Finally, Cleary *et al.* (1979) pointed out that the H I filament that they proposed as a candidate for the extension of Loop I at southerly latitudes (section 3) follows the directions of the optical polarization vectors in the area. They suggest a likely distance of about 115pc from a sudden increase in polarization percentage.

4.3 A runaway star connected with Loop I ?

Berkhuijsen *et al.* (1970, 1971) drew attention to ζ Oph, an 09.5V high velocity star at a distance of $\approx$ 170pc which is one of the three runaway stars within 350pc of the sun. Its proper motion could have taken it close to the centre of Loop I some 3×10^6 yr ago. It is of interest that some recent SNR models have derived similar ages for the loop (Iwan 1980). If in fact this star has been liberated from a binary system in the supernova outburst that produced Loop I, then the loop will be centred

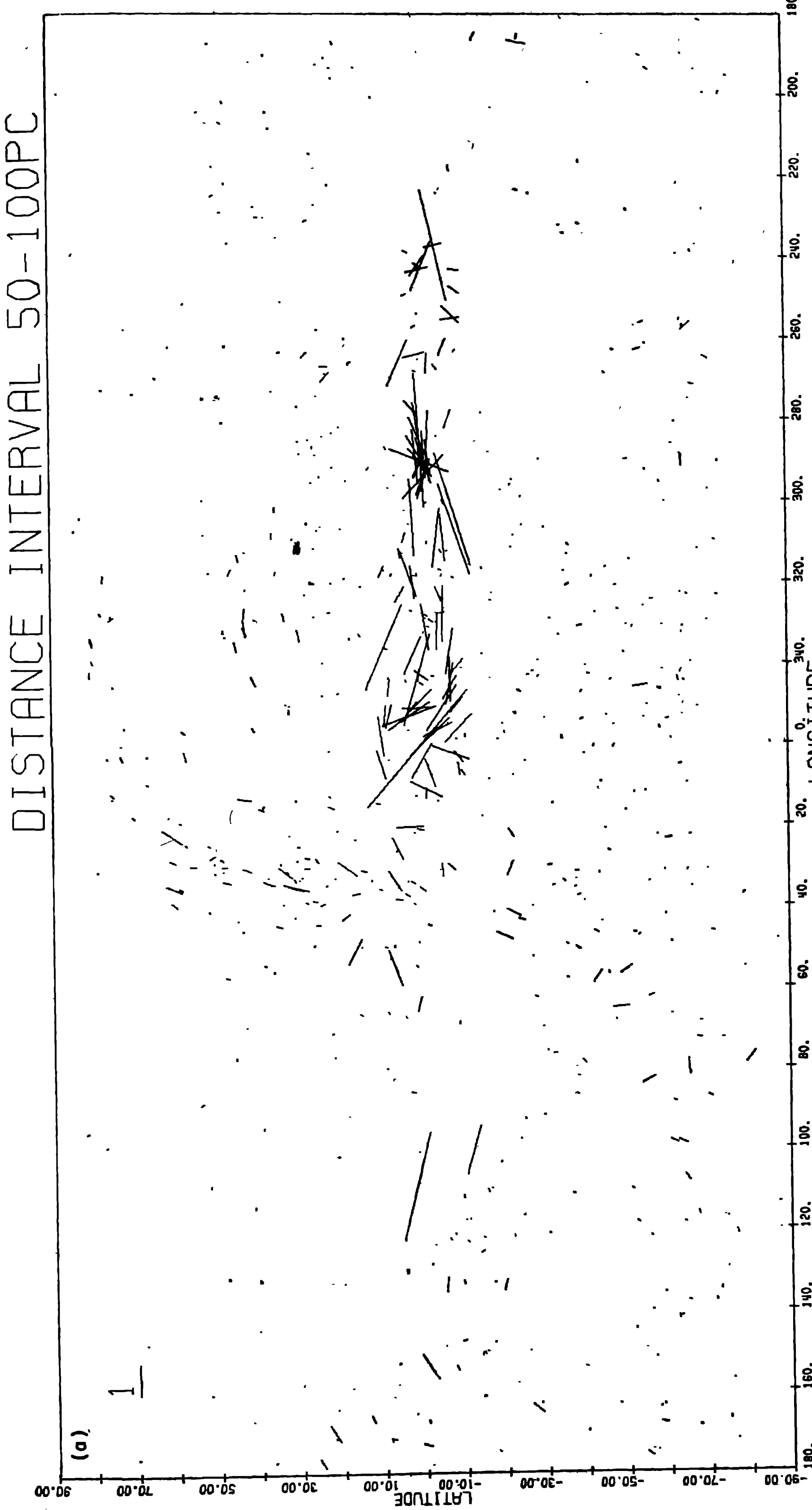

Figure 7. The E-vectors of optical linear polarization plotted in Galactic coordinates. The length of each line is proportional to the percentage polarization with the scale being marked in the top left-hand corner. The diagram contains stars with distances between 50 and 100 pc. (Axon & Ellis 1976).

on the Sco-Cent association. Berkhuijsen *et al.* claimed that the primary of the binary must have been very massive and suggested that the outburst may have been particularly energetic. Attention is drawn to an alternative, if in some ways similar, origin for the high velocity of ζ Oph recently suggested by Rajamohan & Pati (1980).

5. X-rays from Loop I

Shklovski & Sheffer (1971) made the prediction that if the Galactic loops are SNRs, then they should be emitters of soft x-rays. They added, however, that a detailed correlation between radio continuum and x-ray emission would not necessarily be expected. Further, these authors made an examination of the results of the x-ray study of Bowyer *et al.* (1968) and suggested that there was an enhancement of 205–280 eV radiation coincident with spur regions.

Bunner *et al.* (1972) produced remarkable maps of the x-ray emission from the NPS in two energy windows (figure 8). Both maps (resolution $\approx 8°$) showed a high intensity ridge close to, but somewhat inside, the RCNPS. Clearly, the x-ray NPS (XNPS) was of somewhat smaller radius than the radio continuum feature. In the 500 eV to 1 keV window the XNPS emission was reasonably constant with latitude, while for energies of < 284 eV the emission decreased with decreasing latitude. It was considered that this effect could possibly be due to a latitude dependence in the interstellar absorption caused by the fall in gas density away from the Galactic plane. If this were to be the case, the distance to the XNPS would be some 100pc or greater. A possible enhancement near the $l \approx 270°$ limb of Loop I may also be present in the low energy map.

De Korte *et al.* (1974) confirmed the enhanced soft x-ray emission from the XNPS, finding evidence of this between $b = 15°$ and $85°$. At high latitudes they found good positional agreement between the XNPS and the RCNPS, while below $b = 50°$ they agreed with Bunner *et al.* that the x-ray feature lies inside the RCNPS. Cruddace *et al.* (1976) obtained four scans across the NPS at different latitudes, two of which also intersected Loop IV. They recorded data in five energy bands between 180 eV and 6 keV. Their conclusions can be summarised as follows:

(i) Below 3 keV localised enhancements were seen on all scans. These were clearly connected with the NPS for the two lower latitude cuts ($b \approx 32°$ and $47°$), whereas on the two high latitude scans the emission could be from either Loop I, Loop IV or both, the low resolution making exact identification impossible.

(ii) On the two lower latitude scans, the maximum of the x-ray intensity is about 10° inside the radio continuum ridge peak.

(iii) At $b \approx 47°$ the angular displacement of the x-rays from the RCNPS becomes greater as the energy increases. The authors tentatively suggest that this may be owing to the expected decrease in temperature behind the shock of an SNR as its velocity falls during expansion.

(iv) The minimum intensity inside Loop I is higher than outside, as would be expected from a shell source of x-rays.

Burstein *et al.* (1977) also detected the XNPS in the energy band between 100 and 850 eV. They noted a feature of greater x-ray hardness at ($\approx 20°$, $\approx 25°$), previously

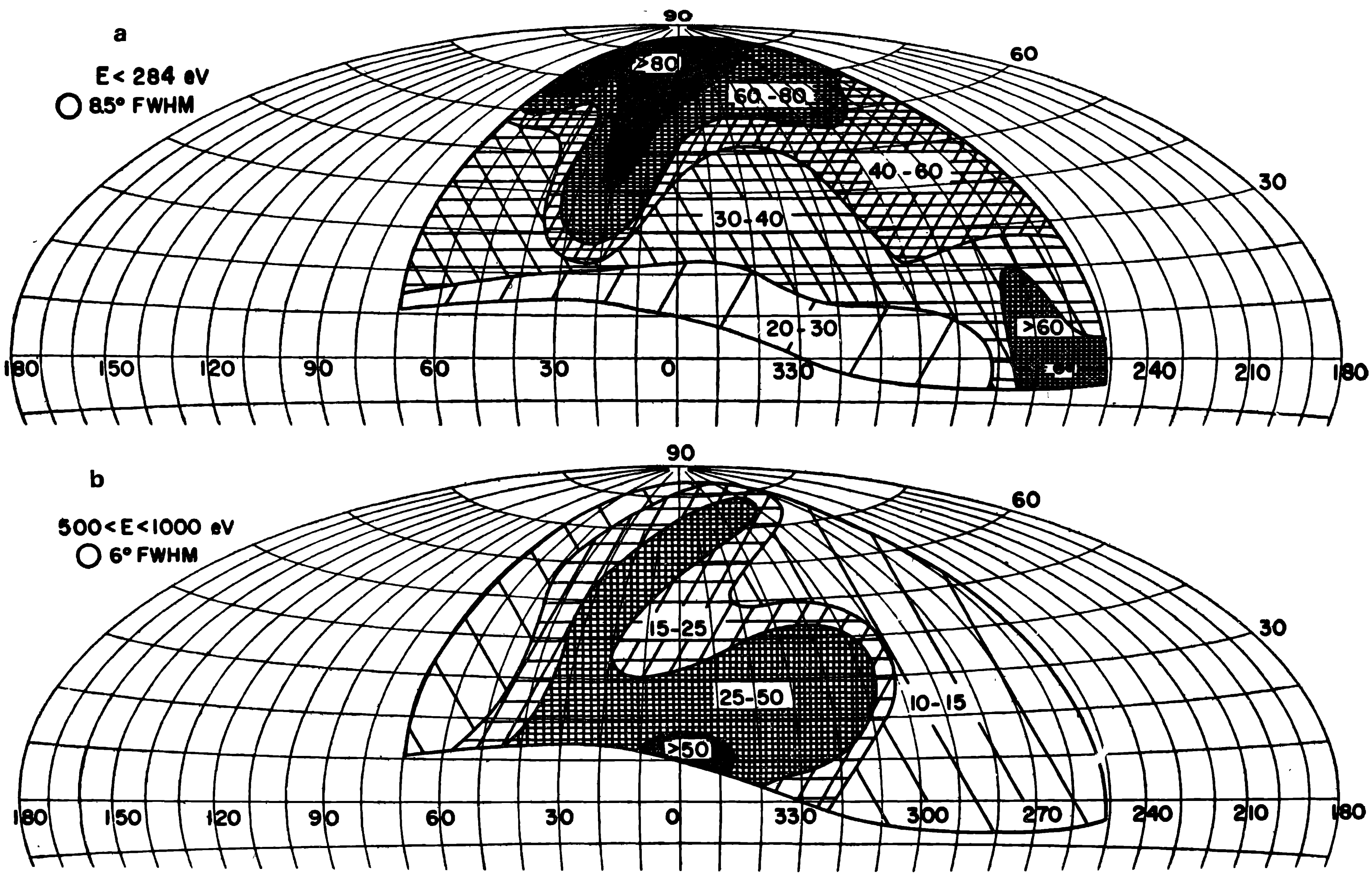

Figure 8. X-ray intensity isophotes for (a) data with energy < 284 eV and (b) data with 500 < energy < 1000 eV. (Bunner *et al.* 1972).

seen by de Korte *et al.* This is often called the *Ophiucus hot-spot* and it is not clear if it should be associated with the NPS (e.g. Borken & Iwan 1977).

Hayakawa *et al.* (1977) scanned their detector along a great circle path perpendicular to the Galactic plane and lying along $l = 150°$ and 330°. In the window 0.4–1.6 keV they found an enhancement at $l = 330°$ between $b = +60°$ and $+80°$, on and just inside the RCNPS. A further, fainter enhancement was visible at (330°, −40°) which the authors believed to be southern extension of Loop I. Below 400 eV these enhancements could not be seen. Like Cruddace *et al.* before and Iwan (1980) and Davelaar *et al.* (1980) later, they too claimed that there is a general excess of emission towards the central regions of Loop I. The authors constructed energy spectra for a number of positions along the scan and found the spectra inside and outside Loop I to be different. Each spectrum inside the loop was characterised by a hump peaking at $\approx$ 650 eV. They fitted this spectrum with a two component model representing the *foreground* x-rays and the Loop I emission. At the upper crossing point, the Loop I spectrum can be fitted well by that of a thermal plasma of depleted abundances with a temperature of about 3.1×10^6 K and no foreground absorption. Hayakawa *et al.* believed that the major contribution to the 650 eV hump came from emission lines of O VII and O VIII.

In a further study of the spectrum of XNPS emission, Inoue *et al.* (1980) analysed spectral data taken at (30°, 25°) and shown in figure 9. Attempts to fit either a power law spectrum or that of free-free emission gave no fit with significance level greater than 0.5%. They then compared the spectrum with that expected from a thin, hot plasma having cosmic abundances. Again no fit of greater significance was obtained, mainly because of discrepancies due to the 650 eV hump. The best fit gave a temperature of 3.2×10^6 K, the same temperature as they got for a fit to the Cygnus Loop x-ray spectrum. They noted that the XNPS spectrum looked rather similar to that of the Cygnus Loop, although there is a significant difference near 800 eV which they put down to a different emission line spectrum. The authors attempted a spectral decomposition of the 650 eV excess assuming a temperature of 3.2×10^6 K and considering a spectrum made up of lines of C, N, Ne, O and Fe. A reasonable fit can be made, although such features as overstrong lines of N compared to those for cosmic abundance may imply a multi-temperature structure. The derived Fe XVII line intensity is weaker than expected and Inoue *et al.* suggest that there is a lower than cosmic abundance of this element, perhaps due to being locked up in dust grains. This Fe defficiency is not found for the Cygnus Loop. They suggest that this, and the lack of optical filaments on the NPS, may be evidence for a lower density of the interstellar medium near the NPS compared to the Cygnus Loop. Rocchia *et al.* (1981) have recently reported another spectral study of the XNPS. Fitting a hot plasma model with normal abundances they derive a temperature for the XNPS of 3.3×10^6 K, remarkably close to the values obtained by the Japanese workers.

A rather thorough study of the XNPS has been presented recently in papers by Borken & Iwan (1977) and Iwan (1980). These authors presented maps with a resolution of about 3° covering the NPS for $b = 25°–58°$ in energy ranges between 180 eV and 2 keV. All maps show the XNPS to consist of two concentric ridges lying inside the RCNPS. The outer ridge is the stronger at higher latitudes

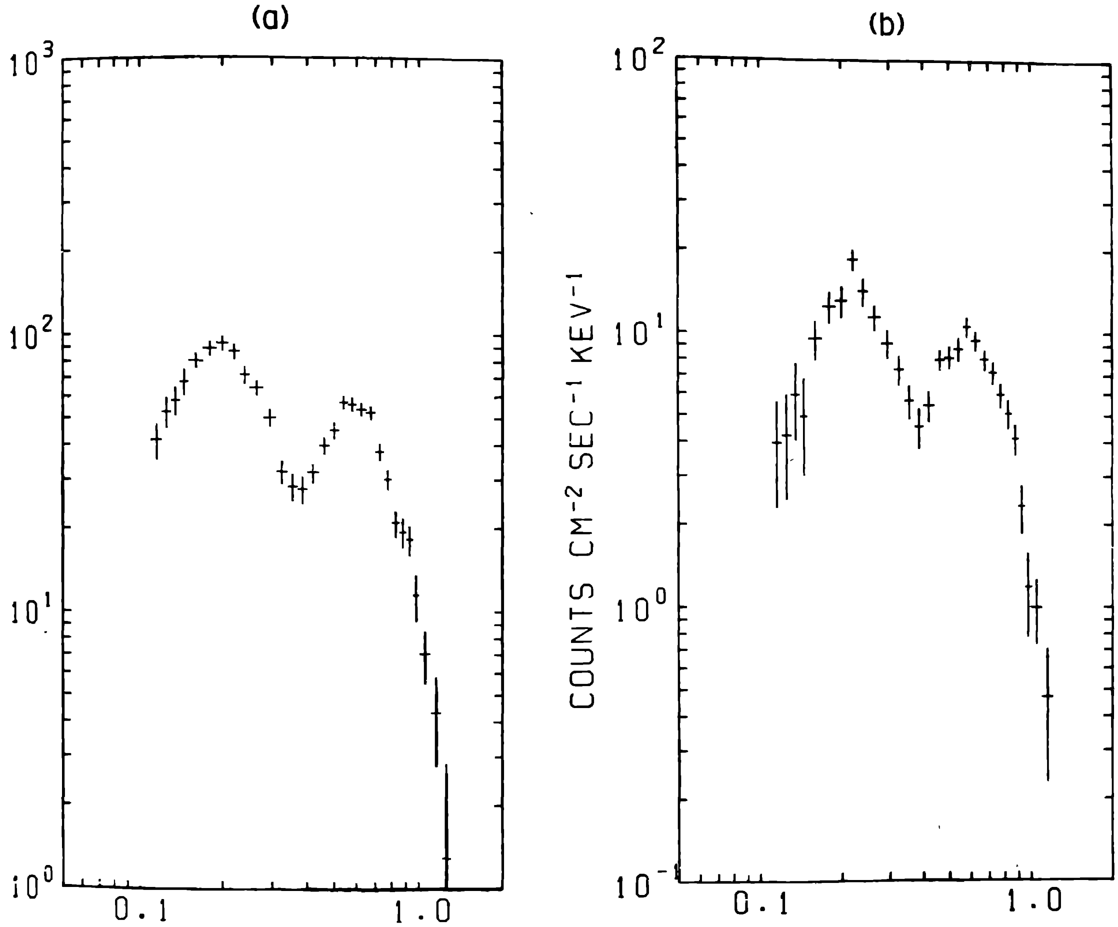

Figure 9. (a) The observed x-ray energy spectrum of the NPS at (30°, 25°) after subtracting a diffuse power-law component. (Inoue *et al.* 1980). (b) A similar spectrum for the Cygnus Loop.

and the inner at low latitudes. Also, the outer ridge displays a spectral hardening towards the interior, while both ridges harden with decreasing latitude. Both these effects confirm earlier suggestions described above. The difference of the radii of the two ridges is, on an average, about 7°.5, with the outer ridge lying 1°.5–3°.5 interior to the RCNPS. The centres of the best fit small circles to the ridges are consistent with their being concentric with the RCNPS.

In interpreting the spectral properties of the x-rays, Iwan (1980) used a model of a hot plasma with normal abundances in collisional equilibrium. She found the x-ray hardening across the outer ridge to be consistent with a temperature change from 3×10^6 K to 3.5×10^6 K over some 2° perpendicular to the NPS. On the outer ridge she derived an emission measure of $1–2 \times 10^{-2}$ cm^{-6}pc. The increasing intensity of the XNPS towards low latitudes in the two higher energy windows is taken to imply an increasing gas temperature, emission measure, or both towards the Galactic plane, while the decrease in the low energy window implies increasing absorption. A neutral hydrogen column density difference of 4×10^{20} cm^{-2} at $b = 30°$ compared to $b = 53°$ was derived. This is compatible with the increase found in the low velocity H I by Heiles & Jenkins (1976). Iwan claimed that Berkhuijsen *et al.* (1971) calculated a surface density for an H I shell of $\approx 2 \times 10^{19}$ cm^{-2}, so such a shell alone could not be responsible for the implied absorption. In practice, Berkhuijsen *et al.* quote a mean surface density of $(2 \pm 1) \times 10^{20}\,\mathrm{cm}^{-2}$ (section 3) and Iwan's conclusion may require reconsideration.

Iwan (1980) also pointed out an interesting correlation between the ultraviolet absorption lines of Lyα and H_2 molecules in nearby stars, and the NPS. The derived surface density of neutral hydrogen makes a transition from $< 1 \times 10^{20}\,\mathrm{cm}^{-2}$ to $> 5 \times 10^{20}\,\mathrm{cm}^{-2}$ at a distance of about 100pc towards the NPS. In other directions this surface density is $< 2 \times 10^{20}\,\mathrm{cm}^{-2}$ up to hundreds of parsecs. Iwan added that a similar pattern is to be seen in stellar reddening measurements and took this to mean that the low velocity gas of Heiles & Jenkins (1976) is at about 100pc and situated between the sun and the NPS if it is to absorb the soft x-rays. The above cautionary note should perhaps be borne in mind.

Davelaar *et al.* (1980) achieved the highest resolution yet available on the NPS (15′ in one direction) with a low energy response down to 60 eV. They took two scans across the RCNPS at $b = 25°$ and 75°, using the high resolution to study the brightness distribution of the XNPS and its relation to the RCNPS. On both scans emission was detected in the energy range 0.6–1 keV lying inside the RCNPS and of width $10° \pm 1°$ at $b = 75°$ and $\geqslant 15°$ at $b = 25°$. The authors presented spectra from the XNPS at $b = 25°$ and 75°, as well as from a point inside Loop I at $b = 55°$ and a comparison spectrum from outside the loop. All three Loop I spectra showed the now familiar 650 eV-hump, which was not seen in the comparison spectrum, and again gave temperatures close to 3×10^6 K. On both scans the 0.6–1 keV radiation had its centre of gravity some 5° inside the peak of the RCNPS. The 60–250 eV intensity profile at $b = 75°$ showed a steep rise inside the radio emission with two quasiunresolved peaks separated by about 1°.5 along the scan direction. The authors warned that either or both of these peaks could be point sources. However they found, consistent with previous observers, that the x-ray ridge at low energies is closer to the RCNPS than at high energies.

Finally, Singh *et al.* (1981) have made x-ray intensity maps that cover the $l \approx 270°$ end of Loop I and the position of its small circle at southerly latitudes, as well as the southern limb of Loop IV. In the 0.4–1 keV range they detect brightening on and inside Loop I (270° to 300°, 20° to 40°), in coincidence with the boundary of Loop IV (320° to 350°, 20° to 40°), and on part of the hypothetical southern extension of Loop I (300° to 315°, −20° to −30°).

6. Possible γ-ray evidence ?

Morfill *et al.* (1981) have suggested that the influence of the hypothetical Loop I SNR may be apparent in the γ-ray source CG 353 + 16. This source has been associated with the ρ Ophiucus interstellar cloud at a distance of 160 ± 10pc. The γ-ray flux from the cloud is some three times that predicted by the theory of cosmic ray interaction with interstellar material, if the cosmic ray intensity is the same at ρ Oph as in the solar neighbourhood. The explanation of this favoured by the authors is that the cosmic ray flux at ρ Oph is a factor of three higher than near the sun. They point out that the increased cosmic ray flux could be due to the acceleration of Galactic cosmic rays by an old SNR shell that is currently interacting with the cloud. They further propose that the previous passage of an even older SNR may have triggered star formation in ρ Oph, while the Loop I SNR, expanding in a hot tenuous background plasma, has now reached the cloud bathing it in an enhanced cosmic ray flux. It should perhaps be stressed that while the authors prefer this theory to explain the CG353 + 16 anomaly, it is not the only one that they put forward.

7. The many theories of the NPS and Loop I

Throughout the past 25 years there have been a sucession of suggestions as to the nature of the NPS and Loop I. In the early days only the bright arc of the RCNPS was known and most of the theories from those times no longer fit the present wealth of observational data. An inevitable result of this mass of observational material has been the increasing sophistication required of the theories. While today the models that seen most compatible with measurement are variants of the theory that the remnant of an SN outburst is the principal actor in this cosmic drama, there is still considerable room for disagreement. The age and stage of evolution of the remnant, the circumstances determining the emission in the various wavelength ranges and the environment in which the shell is expanding are all points of some uncertainty. In the present section we will briefly summarise the many primary theories suggested over the years to account for Loop I/NPS and will highlight some of the difficulties which each have encountered.

Some of the initial theories ran into difficulty as the RCNPS was not only considered to be a complete object in its own right, but was originally thought to lie along a great circle in the sky. For example, Johnson (1957) suggested that the NPS might be the manifestation of a collision between our own Galaxy and another spiral galaxy. Tunmer (1958) believed the NPS to be a great circle *belt* of emission perpendicular to the Galactic plane. This she explained as a rainbow effect caused by the propagation properties of cosmic ray electrons having different pitch angles to the magnetic field along the spiral arm and the directional properties of synchrotron emission. A third theory that is no longer compatible with the known geometry of the NPS is that of Oda & Hasegawa (1962). These authors proposed that a supernova in the local spiral arm has injected relativistic electrons into a cigar-like deformation of the local magnetic field structure projecting north of the Galactic plane.

Brown *et al.* (1960) produced two alternative theories to account for the RCNPS. They first suggested the presence of a short minor arm or interarm link between the Orion and Sagittarius spiral arms. They suggested that this feature was parallel to the Galactic plane, but at a height of about 300pc above the plane, and subtended an angle of about 15° at its closest approach to the sun. While they were able to reproduce the general geometry of the RCNPS, and the required radio emissivity of the arm was not incompatible with that produced by other spiral arms, a number of objections make this idea unlikely today. The extreme circularity of the RCNPS and Loop I, the existence of the H I NPS and XNPS on opposite sides of the RCNPS and the apparent association of the NPS with both interior and exterior ridges may be mentioned as specific difficulties.

A recent attempt to revive the interarm link model has been made by Sofue (1973, 1976). He suggested that the radio spurs are *bank-shaped* radio emitting regions above spiral arms and inter-arm links. He noticed an area of high optical obscuration at $l = 20°$ to $30°$, $b \geqslant 0°$, where the RCNPS approaches the Galactic plane, and suggested that areas of high obscuration in the Milky Way are due to the tangential viewing of the galactic shocks in which gas and dust are being compressed. In his picture, the *radio banks* project up from the spiral arms into the halo, being inflated by the instability of the interstellar magnetic field to cosmic ray pressure. He too associates the NPS with a local interarm link at $l \approx 25°$. Sofue's model seems open to the same criticism as that of Brown *et al.*

The second model of Brown *et al.* has stood the test of time considerably better, although many additions and modifications have been incorporated over the years. They suggested that the NPS is the brightest segment of an SNR and predicted that the outer edge of the RCNPS should be sharper than the inner edge, while the area inside the spur should show more intense emission than occurs outside the object. These predictions seem well confirmed by both the radio continuum and x-ray emission. Since its proposal, this theory has received a fair amount of criticism. This, as well as its notable successes in explaining many of the features of Loop I, will be examined in detail in the next section.

In a radically different vein, Rougoor (1966) attempted to unify the various loops and spurs into one object. He noted that, on the then-available evidence, it was possible to imagine that Loop I crossed the plane in such a way as to join smoothly into Loop II, this in turn joining Loop III, which itself ran into the southern spur at $l \approx 80°$. He suggested that the whole structure could represent a helix with its axis pointing towards (110°, 0°). Mathewson (1968) expanded on the idea of unification of the loops. In his examination of the polarization of starlight he found that he could reproduce the overall pattern of polarization position angles by a model in which the local magnetic field has a helical structure. He noted that the spur ridges and regions of strong radio polarization follow the *flow patterns* of the optical polarization vectors and concludes that the spurs and loops are tracers of the helical magnetic field structure of the local spiral arm. A number of objections can be raised to these theories. First, strong evidence has been advanced (Berkhuijsen *et al.* 1971) that Loop III crosses the plane on its small circle path rather than joining Loop II at $l \approx 150°$. Similarly, Sofue & Reich (1979) showed the RCNPS to continue on its small circle to very low latitudes, diverging considerably from Mathewson's predicted path. The exact mechanism whereby the local helical field should manifest itself as the filamentary loops was never clearly defined and it is also not clear how the model could account for the XNPS.

Bingham (1967) put forward an idea that would account for the suggested special relationship between the loops and the Galactic plane. He suggested that the loops could be a consequence of the instability of the interstellar magnetic field to cosmic ray pressure (Parker 1965). Bingham proposed that via this mechanism, loops or bubbles of magnetic field could rise from one side of the Galactic plane with expansion velocities of some 100 km s^{-1}. As just noted, however, Loop III appears to cross the plane, while the full circle of Loop IV is contained within the northern hemisphere. If all loops are similar, this would remove the fundamental reason for invoking this picture. Also, as detailed in section 3 and 5, it has been suggested that Loop I can be traced around an almost full circle through H I and x-ray observations. Another model for Loop I employing distortion of the local magnetic field was proposed by Clube (1968). He believed that Gould's Belt distorts the local spiral arm field, causing the field lines to rise more or less perpendicularly to the north of the plane in the first longitude quadrant. These field lines would have a radius of curvature of about 100pc and be observationally evident as the RCNPS. Once more, the sharply angled approach of the NPS to the plane presents difficulties, and how to explain the hot plasma of the XNPS is not clear.

Brandt & Maran (1972) found themselves dissatisfied with the SNR hypothesis of Brown *et al*. Noting that the Lupus Loop SNR (Milne 1971) is rather near the centre of Loop I, they proposed that Loop I is a fossil Stromgren sphere (FSS) induced by radiation from a supernova event, rather than being formed via supernova ejecta. They suggested that the object is in a *hot ring* stage in which the centre has cooled but partially ionized gas exists at the edge of the object. They expect expansion due to the pressure inbalance between the hot ring and the surrounding interstellar medium. Then Alfven waves, or a shock originated by the expansion, would compress the adjacent magnetic field and cosmic ray gas, enhancing the radio synchrotron emission through the mechanism suggested by van der Laan (1962). This idea was reexamined by Kafatos & Morrison (1973). They computed that the initial shock wave around the FSS would have a greater than thermal velocity and suggested a value of order $75\,\mathrm{km\,s^{-1}}$. This would give a temperature of $\approx 10^5$ K behind the shock. They also estimated an age of $> 10^5$ yr for the NPS, concluding that the SNR that caused the FSS would probably be already undetectable. Kafatos & Morrison noted that the temperature needed to produce thermal x-rays to explain the XNPS would be higher than could be accounted for by the FSS and added that if their theory is correct then the x-rays would have to be emitted by the synchrotron process. As detailed in section 5, the spectrum of the XNPS seems to be quite consistent with that expected from a thermal plasma and not with the power law expected from synchrotron radiation. This seems to be the biggest difficulty in trying to explain Loop I as a FSS. In respect of Brandt & Maran's remarks on the Lupus Loop, note that the most probable distance to that SNR from the surface brightness-linear diameter relation of Milne (1979) is four times the likely distance to the centre of Loop I, derived using the optical polarization of starlight.

Sofue (1977) proposed a totally different theory for Loop I. This came about almost as a by-product of his ideas on the formation of the 3 kpc expanding spiral arm. He envisaged isotropic MHD waves from the Galactic centre propagating through the halo and disk of the Galaxy and showed that these would converge with high efficiency into a ring in the disk. For his model, at $t > 10^8$ yr some 80% of the energy of the waves would converge in the disk at about 3.5 kpc, while the remainder would expand quasispherically into the halo forming an immense shell structure. Sofue believed that the position where the NPS small circle cuts the plane, (21°, 0°), indicates that it and the 3 kpc arm are connected. He produced synthetic contours of the intensity expected from his hypothetical shell and showed that below $b \approx 60°$ these do not look unlike the RCNPS. Above this latitude he has problems in reproducing the form of Loop I. To the present author the major problem with this picture is the strong evidence that Loop I is local. Evidence from x-ray, H I, linear polarization of the radio continuum and optical polarization of starlight would seem to speak against the loop having Galactic dimensions.

Recently, a variant of the SNR hypothesis has been suggested by Weaver (1979). He considers the H I emission of Loop I and derives a centre of curvature in the direction (331°.3 ± 1°.3, 14°.0 ± 1°.4). He also gives a position for the radio centre of Loop I of (336°.0, 24°.0) with quoted errors of less than 2°. He uses these to conclude that the centres of the radio continuum and H I features differ in direction by more then 6σ. This suggests to him that the origins of the H I and radio filaments must be in different events. He points out that the centre of the Sco-Cent OB association is at (330°, 15°) at a distance of 170pc and that the association contains some 40 stars of mass 10–20 $M_\odot$ and age 1–2 × 10^7 yr. Weaver proposes that the massive stars in the association produce strong stellar winds which have inflated a bubble of gas and dust. Left-over material from star formation had previously been drawn out into line-like formations parallel to the Galactic plane by differential Galactic rotation. These structures would have contained an embedded magnetic field parallel to their length. These would later be swept up by the expanding bubble of wind driven gas, compressed radially and stretched on the surface of the bubble to produce the H I filaments seen in Loop I. The near side of the bubble would currently be very close to the sun and Weaver computes the mass of the bubble as $\approx 10^6 M_\odot$, with a diameter of $\approx$ 300pc. He believes the H I observations to indicate an expansion velocity of 2 km s^{-1} and derives an energy for the bubble of $\approx 10^{50}$ erg.

Continuing, Weaver (1979) suggests that the radio continuum is from the *Loop I SNR* caused by the subsequent explosion of one of the more massive stars in the Sco-Cent association. This has expanded in the hot, uniform, low density region swept out by the expanding bubble, permitting it to expand to a large radius and yet be closely spherical. He considers that the SNR is currently just encountering the inner surface of the H I bubble and where they interact velocities of up to 50 km s^{-1} are found. Considering this theory, one is struck that it was devised largely because of Weaver's belief that the radio and H I centres of Loop I do not coincide. It is however to be noted that Berkhuijsen *et al.* (1971) gave the radio continuum centre of Loop I as (329°.0 ± 1°.5, 17°.5 ±3°.0) and that this differs from the H I centre of Weaver by little more than 1σ ! In addition, Heiles *et al.* (1980) have recently revised the likely expansion velocity of the H I associated with Loop I up from $\approx$ 3 km s^{-1} to $\approx$ 30 km s^{-1}. This would imply revising upwards by two orders of magnitude Weaver's derived energy for his bubble. Whether the stellar winds of the Sco-Cent association would be capable of supplying the necessary 10^{52} ergs is an open question.

8. The SNR model of Loop I

8.1 Criticism of the hypothesis

Since its original proposal by Brown *et al.* (1960) the SNR model for Loop I in particular, and the Galactic loops in general, has been the subject of considerable criticism and modification. A number of variants of the basic theme have been proposed with varying degrees of success in compatibility with the observational data. We shall begin the present examination of the SNR hypothesis with a generalized consideration of the criticism it has received and of some of the answers to these provided by its proponents.

Among the most powerful criticism that the SNR model must attempt to answer are the following :

(i) Seaquist (1968) pointed out an apparent difficulty with the SNR hypothesis when he noted that the early surface brightness-linear diameter ($\Sigma - D$) relation of Poveda & Woltjer (1968) implied a distance to the tangential point of the Loop I shell that was considerably less than the 100 $\pm$ 20pc derived from optical polarization by Bingham (1967). Berkhuijsen *et al.* (1971) expressed reservations concerning the extrapolation of the relation to deal with an object that is considerably fainter than any SNR used to derive the formula. Nevertheless, Berkhuijsen (1973) readdressed the problem and showed, using the most plausible estimates for the distances to the four main loops, that these loops fitted reasonably well on the extrapolation of the then $\Sigma - D$ relation of Ilovaisky & Lequeux (1972). Her best estimate of the distance to the centre of Loop I was 130 $\pm$ 75pc, giving a radius of 115 $\pm$ 68pc for the radio continuum shell, and a distance to the tangential point of 70 $\pm$ 40 pc. Caswell & Lerche (1979) have recently reconsidered the $\Sigma - D$ relationship. Their revised relation gives a likely distance to the centre of Loop I of 80pc, compatible with Berkhuijsen's estimate but implying a closer distance to the tangential point than Bingham obtained. Note, however, that both Spoelstra (1972) ond Seymour (1969) tend to suggest rather closer distances than Bingham. It should also be remembered that any $\Sigma - D$ relation is derived empirically and the predictions for any specific SNR could be considerably in error.

(ii) The proposal that the Galactic loops could be nearby SNR has always raised the preoccupation that the implied density of these remnants may be statistically unlikely (Large *et al.* 1962; Bingham 1967). This problem was particularly acute when it was thought that the loops might be at a similar evolutionary stage to the Cygnus Loop (*e.g.* Davies 1964). Berkhuijsen *et al.* (1971) considered this difficulty and concluded that if the loops were *normal* SNR, then the probability of finding so many near the sun was only acceptable if they represent old, low velocity SNRs of typical diameters $\approx$ 130pc, ages $\approx 7 \times 10^5$ yr, with distances between their centres and the sun $\approx$ 90pc. Caswell & Lerche (1979) agreed that for the distances derived from their $\Sigma - D$ relation the density of loops is acceptable if they are several hundred thousands of years old. Ages of this order are suggested for the loops by their empirical SNR $\Sigma - t$ relation.

(iii) Bingham (1967) computed that at a radius of 150pc, the Cygnus Loop would be expected to have an expansion velocity of $\approx 0.5\,\mathrm{km\,s^{-1}}$ were its shell to expand with conservation of linear momentum. X-ray observations of the Cygnus Loop suggest, however, that the SNR is currently in the adiabatic phase of its expansion and direct application of momentum conservation could give a gross underestimate of the velocity expected at a given radius. Further, the value of the local interstellar medium density is a critical parameter in the evolution of a SNR, and the values near the Cygnus Loop and Loop I could be very different (Inoue *et al.* 1980). Attempts to fit the observed parameters of Loop I to models of remnant expansion are described in section 8.2.

(iv) Bingham (1967), like Rougoor (1966), noted on the basis of the then available evidence that Loops I to III appeared to have a special relationship with the Galactic plane. Their maximum brightness segments are located at lower latitudes and they seemed to approach the plane roughly at right angles, but not cross it. Berkhuijsen *et al.* (1971), however, claim to follow the high latitude end of Loop III across the plane, as was later confirmed by Milogradov-Turin (1972). Also, if correct, Berkhuijsen *et al.*'s suggestion that Loop IV could be similar to the first three loops provides an object completely contained north of $b = 25°$ with its brightest segment parallel to the plane. As detailed above, Sofue & Reich (1979) have demonstrated that the NPS approches the plane not at right angles but on its predicted small circle path. Suggestions that Loop I can be traced at southerly latitudes in H I and x-ray emission would also contradict any special relationship to the plane.

(v) Many authors have considered that the extreme faintness of optical emission associated with the NPS (section 4.1) throws doubt on an SNR origin. The explanation for this faintness is not clear, although the SNR may have expanded in a very low density environment. Many of the age calculations suggest that Loop I if an SNR, is older than most known SNRs and the presence of the H I NPS, an extensive cool component, might mean that its main radiative phase has already passed.

(vi) Berkhuijsen (1973) suggested a diameter for the radio continuum Loop I of 230 ± 135pc. If the Galactic loops are indeed objects of such dimensions, why are other, more distant SNRs of similar diameter not observed? There is indeed a dearth of recognized radio continuum shells of this size. However, it should be noted that the recent $\Sigma - D$ relation of Caswell & Lerche (1979) gives reasonably large diameters for a number of known SNRs. For example, Graham *et al.* (1982) derive a diameter of 110 to 120pc for the Monoceres nebulosity using this formula.

Recently, Downes *et al.* (1981) have discovered a new, large diameter continuum arc which, if an SNR, has a likely diameter of 105–140pc. This object was only revealed by observations of good resolution and the highest sensitivity, demonstrating that the selection effects against the detection of distant, low brightness, large diameter loops are rather severe. A large angular diameter x-ray ring was found recently by Nousek *et al.* (1981). They believe that there is probably radio continuum, H I and diffuse Hα emission associated with the object. While setting a distance to the object is difficult, the $\Sigma - D$ relation applied to the suspected radio emission suggests a diameter of 140 ± 25pc. A decrease in the surface density of the candidate H I emission with increasing latitude, leads Nousek *et al.* to propose that the diameter of the ring may be similar to the scale height of the gas layer. They find no optical filaments down to an emission measure of $\approx 30\,\mathrm{cm}^{-6}$pc but believe there to be diffuse Hα along one edge of the ring at an emission measure of 3–10 cm^{-6}pc. Certainly the proposed characteristics of the object look remarkably like many features of Loop I. The authors suggest that it may be an intermediate object between a conventional SNR and a *radio loop*.

It is of interest that many of the H I shells found by Heiles (1979) could well be the result of a single SNR explosion and have radii of order, or in excess, of 100pc. A sensitive search for radio continuum emission from these shells would be of great interest.

(vii) Many authors have been worried by the extreme circularity of the Galactic loops. If the loops are SNR of radius ≈ 100pc then this is close to the scale height of the gas layer and the decreased gas density at high z might be expected to result in distortion of the spherical symmetry of the shell as it expands. The problem is somewhat eased for Loop I as the large angular diameter implies that the tangential points on the shell delimit an end cap rather than lying on a plane passing through the centre. Nevertheless, this is certainly a major problem that needs consideration by the supporters of the SNR hypothesis.

One possible solution was suggested by Chevalier & Gardner (1974). They made numerical models of SNR outbursts near the plane, taking the density gradient of the gas layer into account. These authors conclude that for a remnant of radius $\approx$ 100pc a spherical shape for the outer part of the shell is entirely likely, but that the site of the outburst would no longer mark the centre of the shell.

(viii) Sofue *et at.* (1974) highlight that at many points on the NPS there appears to be no sudden increase in the optical polarization percentage with distance. As detailed in section 4.2, Spoelstra also found this, although he did note higher polarization in the direction of the NPS than elsewhere, above $b \approx 60°$. Clearly the situation requires further investigation, especially as the studies described in section 9 suggest that the dust grains in at least part of the Loop I shell may have been largely destroyed.

(ix) Sofue *et al.* (1974) also stress that if Loop I is an old, low velocity SNR it should not be capable of heating the gas behind its shock to the temperature of $\approx 3 \times 10^6$ K derived for the XNPS. It should be noted that the x-ray emission comes from the inner volume of the hypothetical shell and it is perhaps possible that it is residual hot gas from an earlier phase of expansion. Borken & Iwan (1977) were the first to suggest the alternative hypothesis that the rear of the shell is being reheated to high temperature by an energetic event. This idea will be described in greater detail in section 8.3.

(x) An early problem for the SNR theory was how to explain the radio continuum ridges associated with Loop I (section 2.1). The most common explanation is still that proposed by Large *et al.* (1966), that the ridges represent corrugations of the spherical shell giving augmented depth within the shell for certain lines of sight.

(xi) The presence of H I in an SNR shell, and its geometry with respect to the radio continuum, are observational facts that require explanation. If the SNR were in the adiabatic phase, then the formation of a thick H I shell is not expected. However it is of interest that Gilovanelli & Haynes (1979) have found a dense H I shell associated with IC443, an SNR usually considered to be in the adiabatic phase. The H I in this object appears to anticorrelate with the strong radio continuum emission, although in terms of position round the shell rather than radially. In later stages of SNR evolution a thick, cool, neutral shell is expected to form (Chevalier 1974) and this would perhaps seem the most likely evolutionary phase for Loop I. The existence of many large H I shells has recently been demonstrated by Heiles (1979) and Hu (1981). The radial offset of the RCNPS and H I NPS is a point that clearly demands explanation and, as described in section 8.3, this problem has recently been tackled by Heiles *et al.* (1980).

8.2 Loop I as a normal SNR

In the early and mid-60s, when the SNR hypothesis of the loops was being first developed, most authors compared the features of these objects with those of the classic, large diameter radio remnants such as the Cygnus Loop. However, since the late 60s, when the distance estimates from optical polarization became available for Loop I, it has seemed more likely that the loops have much larger diameters than the classic SNRs. Consideration of the $\Sigma - D$ relations, and probability arguments concerning the density of loops in the local region of the Galaxy, also suggest SNRs of great size and, possibly, age. Since this realization, a number of authors have addressed the problem of whether a classical SNR could evolve to a configuration that is compatible with the observed properties of Loop I. While there seems little consensus among these authors, especially as to which stage of remnant evolution is the most probable for Loop I, a brief review of the current status is given in this subsection.

Some useful input data is supplied by Haslam *et al.* (1971) using data from Berkhuijsen *et al.* (1971). If the H I NPS were a shell of radius 85–170 pc, they give an H I density in the shell of 0.5–1.0 cm^{-3}, corresponding to densities of 0.05–0.10 cm^{-3} should this H I be uniformly spread over the volume of the object. The mass of the shell would be some 1–5 $\times 10^4 M_\odot$, implying a kinetic energy of 1–5 $\times 10^{51}$ erg were the expansion velocity to be 100 km s^{-1}. For the expansion velocity of 30 km s^{-1} derived by Heils *et al.* (1980) this energy estimate should be reduced by an order of magnitude. It should be noted that the above shell mass is considerably less than the $10^6 M_\odot$ derived by Weaver (1979).

Spoelstra (1972) investigated whether the general appearance of the Loop I radio continuum emission and its linear polarization could be satisfactorily modelled by a simple SNR model. He used the van der Laan (1962) model of emission from an old SNR, assuming a simple shell of thickness 15% of the radius and a magnetic field parallel to the inner surface of the shell. The predicted continuum isophotes were in reasonable agreement with the observations. Although the predicted llnear polarization agreed less well with the measurements, he could account for the apparent change in the magnetic field direction at $b \approx 40°$ (section 2.2) as due to projection effects. Spoelstra (1973) applied the same model to Loop IV, treating it as a separate SNR.

Heiles & Jenkins (1976) considered the status of the H I shell in a Loop I SNR. They suggested that the filamentary structure of the cooled H I gas is a result of density inhomogeneities in the undisturbed preshock medium or to turbulence behind the shock front. In view of this, it is of interest that Rickard & Cronyn (1979) suggested that their region of peculiar scintillation properties at $l \approx 60°$ might be due to enhanced turbulence in the interstellar medium, possibly due to an outer turbulence shell ahead of the main H I NPS.

Cruddace *et al.* (1976) compared their x-ray scans across the NPS with radial profiles computed using the SNR models of Chevalier (1974) and allowing for foreground H I absorption. They derived model profiles both for an SNR in the adiabatic phase and for one in which radiative cooling had just set in in its outer shell. Both the shape and separation of the soft and hard x-rays could be qualitatively reproduced. They concluded that the SNR is unlikely to be expanding adiabatically. Taking the radius of Loop I as 120 $\pm$ 40pc and interstellar densities of 0.1–0.6 cm^{-3}, Cruddace *et al.* deduced from the measured intensities that the SNR probably has an age somewhere between t_c, the age at which it is just entering the radiative cooling phase, and $3t_c$. They pointed out that the object being in the radiative phase would account for the presence of the shell of neutral hydrogen seen as the H I NPS. They computed a most likely age of $1.4–3.8 \times 10^5$ yr, with an outburst energy of $1.5 \times 10^{51}–4 \times 10^{53}$ erg and suggested that this outburst was an SNII, perhaps of unusually high energy.

Hayakawa *et al.* (1977) fitted their measured Loop I x-ray spectrum and intensities to numerical models of SNR and for a radius of 115pc derived that the outburst energy was $\approx 3 \times 10^{51}$ erg, the age $\approx 1.1 \times 10^5$ yr and that the remnant was expanding in a medium of hydrogen density $\approx 7 \times 10^{-3}$ cm^{-3}. They believed that the SNR was in the late adiabiatic phase with an expansion velocity of ≈ 350 km s^{-1}. Later, Hayakawa *et al.* (1979) modified this picture as they concluded that inward heat conduction would mean that the SNR could be better described by an isothermal, rather than an adiabatic, blast wave. For this model they derived a radius of ≈ 45pc, age $\approx 3 \times 10^4$ yr, outburst energy $\approx 2 \times 10^{50}$ erg and an ambient interstellar density $\approx 4 \times 10^{-3}$ cm^{-3}.

Davelaar *et al.* (1980) compared their observed scans across the XNPS with model profiles computed using the work of Mansfield & Salpeter (1974). They made the debateable assumption that the radio continuum ridge represent the shock front of the remnant. Under this assumption, they found the measured distribution to be totally incompatible with an SNR in the radiative phase, but a plausible fit was obtained for the adiabatic phase. They could only account for the large radius if the SNR had expanded in a low density medium. The favoured parameters they derive are radius ≈ 90pc, age $\approx 7.5 \times 10^4$ yr, outburst energy $\approx 3 \times 10^{51}$ erg and an ambient interstellar density of ≈ 0.01 cm^{-3}.

The conclusion of Cruddace *et al.* that the Loop I SN may have had an unusually high energy had been foreshadowed by Bingham (1967). He considered whether the outburst may have been a *super-SN* of unusual energy or perhaps represent multiple explosions. He noted, however, that if all the Galactic loops were to be thus explained then the probability would be very small of the occurrence of a number of such rare events close to the sun in the expected lifetime of a typical loop. Berkhuijsen *et al.* (1971) concluded that if the runaway star ζ Oph were to be associated with Loop I (section 4.3) then the primary of the preoutburst binary pair would have to have had an unusually high mass, suggesting an outburst of exceptional energy.

A rather different model was worked out in detail by Zuzak (1971). He suggested that a typical Galactic loop might be an SNR continually driven by the pressure of cosmic rays produced by a particle source near its centre. These cosmic rays would also provide the relativistic electrons needed to produce the observed synchrotron radio emission. So far, no pulsar, or similar source of energetic particles, has been associated with Loop I or the other loops.

8.3 Loop I as a reheated SNR

Borken & Iwan (1977) and Iwan (1980) believed that there could be major inconsistencies with the existing SNR theories for Loop I. They accept the value for the loop radius of 115 ± 68pc (Berkhuijsen 1973). This large size, together with the presence of an H I shell suggests to them that the object is a very old

SNR, well into its radiative phase. They point out that the larger diameter, classical SNR are only weak x-ray emitters, so why should an even more evolved SNR produce such intense x-ray emission ? It is noted that while the presence of gas at $\approx 3 \times 10^6$ K and the observed x-ray intensities can be explained by the models of Cruddace *et al.* (1976) and Hayakawa *et al.* (1977), these models do not consider the outer shell of H I but take the radio continuum emission to be sited directly behind the shock. Iwan determines the properties of Loop I using parameters derived from the H I observations. Comparison with numerical models of SNR yields an outburst energy of $\lesssim 6.7 \times 10^{50}(D/130)^2$ erg and an age of $\approx 1.9 \times 10^6(D/130)$yr, where D is the distance to the centre of Loop I. For such an SNR she computes that the x-ray intensity should be at least a factor of 20 less than that observed on the XNPS.

These authors propose an interesting modification of the basic SNR model to unify the H I, radio continuum and x-ray features. They suggest that Loop I is indeed a very old SNR, but that it has been reheated by the shock of a second intersecting SNR. Now, the age and outburst energy of Loop I would be given by the above parameters. The properties of the reheating SNR would be given by the observed x-ray emission. Assuming pressure equilibrium between the hot interior of the loop and the observed x-ray ridge, an outburst energy for the reheating SNR of $\leqslant 5 \times 10^{51}(D/130)^{5/2}$ erg was computed. It is perhaps of interest that the above age derived for the main Loop I SNR could be consistent with an association between Loop I and ζ Oph.

Borken & Iwan suggest Loop IV as a candidate for the reheating SNR (see figure 10). They state that Loop IV does not show a dense neutral shell, should not yet be in the radiative cooling phase and may not have lost much energy before reheating the Loop I cavity. It should perhaps be noted that the situation concerning the association of H I and Loop IV is, as yet, not completely clear (see section 3). An alternative candidate as the reheating SNR could be the semicircular feature on

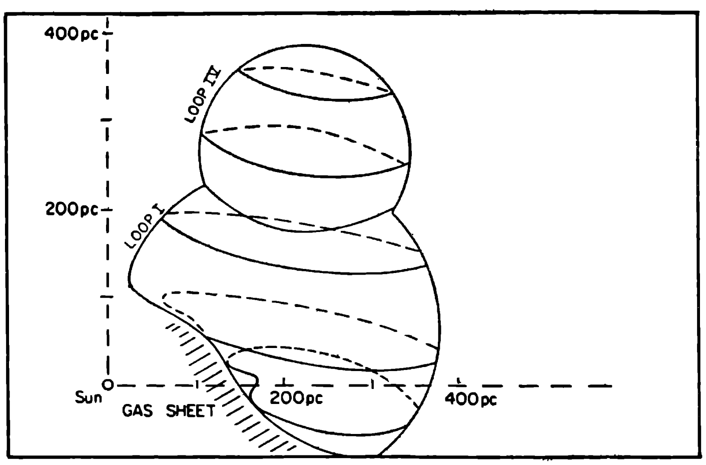

Figure 10. Sketch of Loops I and IV as interacting spheres according to Iwan (1980). Her postulated sheet of gas at ~ 100pc and its distorting effect on the Loop I sphere are indicated. The x-axis lies in the Galactic plane towards $l \approx 330°$ and the z-axis is perpendicular to the plane. The distance scales are labelled at the maximum allowed by the polarization measurements and therefore could be halved.

the RCNPS mentioned in section 2.2 and shown in figure 5. It is situated towards the middle of the arc of the RCNPS and, if a youngish SNR, could possibly be supplying relativistic particles to the shell of the old SNR, as well as reheating the structure. Possible evidence for the separate status of this feature is that Berkhuijsen (1971) showed that the horizontal ridge at $b = 27°$, which is part of the structure, seems to have a somewhat lower spectral index then was typical of the NPS.

The two possibilities of a simple SNR, or a reheated SNR of greater age and lower outburst energy, has recently been considered by Heiles *et al.* (1980). Because of the low apparent expansion velocity found for the H I, they preferred the model of a reheated object. Their specific model is of an H I shell of cooled gas produced behind a spherical shock. The gas at the inner surface of the shell has been ionized either by hot stars within the shell and/or a reheating event responsible for the x-ray emission from the interior of Loop I. They believe the radio continuum emission to come from relativistic electrons trapped in the ionized gas at the back of the shell.

From estimates of the rotation measure within the RCNPS and upper limits to its emission measure (see section 4.1), for a distance to the Loop I centre of 130pc and a shell thickness of the RCNPS of 15% of its radius, Heiles *et al.* set values for the electron density there of $\leqslant 0.4\,\text{cm}^{-3}$ and for the component of its magnetic field parallel to the line of sight of $\geqslant 1.2\,\mu\text{G}$. From attempts to measure Zeeman splitting in the H I NPS and using measured H I column densities, with an assumed path length of 115pc in the H I NPS, they obtain the field component parallel to the line of sight there to be $\leqslant 6\mu\text{G}$, with an H I density $\approx 2\,\text{cm}^{-3}$. The authors argue that these limits are close to the actual values. A consideration of pressure equilibrium between the H I NPS and RCNPS leads them to the conclusion that magnetic pressure dominates in the H I NPS while magnetic, gas and cosmic ray pressures all contribute significantly in the RCNPS.

Heiles *et al.* (1980) note that while the magnetic compression appear higher in the H I NPS than in the RCNPS, it has little radio continuum emission in comparison. They suggest that to provide the excess radio emission from the RCNPS, relativistic electrons are trapped within the ionized region at the rear of the shell by magnetic fluctuations generated by cosmic ray protons. The streaming velocity of the relativistic particles should be roughly equal to the Alfven velocity, which is inversely proportional to the square root of the ion density. This density would be very much greater in the fully ionized inner shell than in the neutral H I NPS, and the low streaming velocity there would imply a much higher density of relativistic electrons in the ionized shell. Heiles *et al.* derive an Alfven velocity in the RCNPS of $\approx 14\,\text{km s}^{-1}$, meaning that a cosmic ray electron would take some 0.5×10^6 yr to diffuse across the 8pc estimated thickness of the shell. In the H I NPS, for an estimated fractional ionization of 0.001, the Alfven velocity should be $\approx 700\,\text{km s}^{-1}$ and the ratio of the cosmic ray densities should be $\approx 50:1$. The authors ascribe the plateau of radio emission outside the RCNPS to the fast diffusing cosmic ray electrons that have escaped from the RCNPS. They account for the partial shell of the radio continuum Loop I by stressing that if an ionised region is to be present to trap the cosmic rays, then there must be an H I shell to ionize. They note that the H I NPS is well formed where the RCNPS is found. For a supply of cosmic ray electrons they presume that relativistic particles are generated inside the shell, perhaps by their accelaration in the shock fronts of energetic stellar winds.

9. Loop I — sculptor of the local interstellar medium

Very recently, two authors (Frisch 1981; Crutcher 1982) have proposed that Loop I may have had a major influence in shaping the general properties of the local interstellar medium (LISM) surrounding the sun. They have studied optical and ultraviolet interstellar absorption lines in the spectra of nearby stars. From these Crutcher derives a velocity vector for the LISM relative to the local standard of rest of 15 km s^{-1} from ($345° \pm 10°$, $-10° \pm 10°$). Temperatures of order 10^4 K are inferred by measurements of Lyα absorption in the nearest stars and a largely neutral, warm interstellar medium is suggested. Out to 5–10pc, the scale size of the LISM, a hydrogen density of $0.05 \leqslant n_H \leqslant 0.2$ cm^{-3} has been derived, while beyond 10pc, n_H tends to be lower. Crutcher proposes that the mass of the warm component of the LISM is 10 $M_\odot$ Both the authors conclude that the refractory elements have abundances not too different from the standard cosmic abundances, but very different from the depleted abundances found in typical diffuse clouds. It is suggested that the dust grains in the LISM have been at least partially destroyed by the passage of a shock front which also accelerated the gas.

Both Frisch and Crutcher draw attention to recent observations of the *interstellar wind* (ISW) which flows into the solar system and is observed through resonantly scattered H and He photons. The ISW has a velocity relative to the local standard of rest of 19 km s^{-1} from about (317°, 2°), similar to the velocity vector of the LISM. Its temperature and density are also similar to those of the LISM and both the authors believe the ISW to represent the warm component of the LISM flowing into the solar system. The similar density of the ISW to the average density of the LISM suggests that the LISM is only mildly clumpy.

Crutcher draws attention to the negative velocity H I feature observed by Sancisi & van Woerden (1970) and the more extensive circular series of HI filaments mapped by Colomb *et al.* (1980) (see section 3). This complex series of filaments, which Colomb *et al.* associate with Loop I, has similar velocities to the LISM and Crutcher concludes that it probably represents a cool, dense component of the LISM. The derived temperature of this gas is < 200 K, with a density of ≈ 30 cm^{-3}. Including the cool, dense cloud component, Crutcher derives a total mass for the LISM of $\approx$ 30 $M_\odot$ and a kinetic energy with respect to the local standard of rest of $\approx 10^{47}$ erg.

Both Frisch and Crutcher note that the directions from which the LISM and ISW are flowing are not far different from the direction of the centre of Loop I. They suggest that the outer shock of Loop I has passed over the sun and both accelarated and heated the local gas, as well as destroying the dust grains. Certainly the possibility that the shock has already passed over the sun is not implausible. There is extensive evidence that both the radio continuum and H I structure connected with Loop I can be seen for a considerable distance beyond the RCNPS, probably to at least 90° from the loop centre. It is of interest that Rickard & Cronyn (1979) suggested that the sun may be within the outer turbulence shell they postulated behind the shock. Frisch also points out that soft x-ray surveys show considerable evidence for a widespread plasma of $\simeq 10^6$ K around the sun (distinct from the

3×10^6 K plasma of the XNPS). The existence of the ISW demonstrates that this 10^6 K plasma is not the nearest material to the sun, although the column density of neutral material in front of this plasma has a surface density of $\leqslant 5 \times 10^{19}$ cm^{-2}. Frisch speculates that this plasma could perhaps be gas heated on passage through the outer shock of the SNR.

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