1973

Giant Loops as Fossil Stromgren Spheres: Their Radio and X-Ray Emission

Menas Kafatos
Chapman University, kafatos@chapman.edu

P. Morrison
UNIV ILLINOIS

Recommended Citation

Kafatos, M., Morrison, P. (1973) Giant Loops as Fossil Stromgren Spheres: Their Radio and X-Ray Emission, *Astronomy and Astrophysics* Vol. 26: 71-77. Retrieved from http://adsabs.harvard.edu/full/1973A%26A....26...71K

Giant Loops as Fossil Stromgren Spheres: Their Radio and X-Ray Emission

Comments
This article was originally published in *Astronomy and Astrophysics*, volume 26, in 1973.

1973A&A....26...71K

Astron. & Astrophys. 26, 71–77 (1973)

Giant Loops as Fossil Strömgren Spheres: Their Radio and X-ray Emission*

M. C. Kafatos
Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder

P. Morrison
Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge Massachusetts

Received July 17, revised March 9, 1973

Summary. The loops are examined as radio and soft X-ray sources under the assumption that they are objects related to the Gum Nebula but much older than it. The loop diameters are likely on the scale of 100 pc or more, as reported recently. This is naturally understood with the fossil Strömgren sphere model. Further progress in understanding the origin of the loops depends on the resolution of certain observational issues.

Key words: radio loops – shock region – fossil Strömgren spheres

I. Introduction

The existence of the four very large, shell-shaped features known as galactic spurs or loops was established about ten years ago. They were first found in the radio continuum; since then they have been studied in the 21-cm line and recently in the soft X-ray region, well under 1 keV. Faint optical nebulosities associated with loops I and II have been observed in Hα. Even though these objects have been studied so extensively, their theoretical interpretation presents numerous problems still. The original suggestion of Hanbury Brown *et al.* (1960) that they are very old supernova remnants meets with serious difficulties: if they are objects like the Cygnus Loop, they are too numerous to be accounted for by the known rate of supernova outbursts (e.g. Bingham, 1967); if they are much older and farther away, hence much larger than the Cygnus Loop, particularly strong explosions have to be evoked, e.g. a rare type III Zwicky supernova explosion (Berkhuijsen *et al.*, 1970). Zuzak (1971) therefore assumes rather that a continuous source of energy now supplies the loops. He holds that the loops are driven by means of cosmic rays emitted by some source near the center, presumably pulsars. There hypothetical sources, however, have not yet been discovered. Parker's (1966) suggestion that bubbles appear in the magnetic field because it is unstable to cosmic ray pressure needs more examination. Mathewson (1968) suggested that a helical component of the interstellar magnetic field is responsible for the radio spurs. This suggestion however has recently been criticized by Manchester (1972). Brandt and Maran (1972) have suggested that the loops are fossil Strömgren spheres produced by supernova explosions, similar to the Gum Nebula but older than it. We here examine this last hypothesis and its consequences. We also present critical tests which might help to establish the real nature of the spurs.

II. Observations

Haslam *et al.* (1971) have written a detailed review of the observations; one should refer to their article for further information. We review here in brief the observational evidence most useful in the subsequent theoretical analysis.

Various authors (Large *et al.*, 1962; Haslam *et al.*, 1964; Caswell *et al.*, 1967; Salter, 1970) find that all four loops are very nearly circular as viewed by radio (r.m.s. deviation ~ 1 degree). If this is a fact, it is remarkable in view of the likely large size of the loops. Each loop can be traced about halfway around its circumference (e.g. Large *et al.*, 1962). In the case of Loop III the small-circle path can be followed across the galactic plane (Haslam *et al.*, 1970). The magnetic lines of force are tangential to the loop for Loop I (Bingham, 1967) while the radio polarization is perpendicular to the loop in the higher-latitude part: In the portion at lower-latitude ($b < 40°$) the polarization is parallel to the loop (Spoelstra, 1971). Haslam *et al.*, (1971) suggest that the radio emission is by the synchrotron process. The spectral index might be 0.7.

---

* Supported in part by National Science Foundation Grant GP-30860 X and by NASA Grant NGF 22-009-021.

Faint visible nebulosities surround Loops I and II. The filament around Loop II has no proper motion perpendicular to the radio ridge greater than 0.5″ per annum (Elliott and Meaburn, 1970).

There is a spur (Berkhuijsen *et al.*, 1970) in the neutral hydrogen distribution as well, which lies close to Loop I; this H I feature is about 5° wide; the surface density of hydrogen within it is $\sim 2 \times 10^{20}$ atom/cm^2. Fejes (1971 a, 1971 b) has observed an H I spur as well near Loop IV. He finds that expansion of the gas with velocity about 30–40 km/s is needed to account for the observations.

The most critical parameter for a model is the linear size of the loops. So far estimates of the size exist only for Loops I and II. Loop I can be detected (Seymour, 1969) in an analysis of interstellar polarization data. By examining stars lying within 110 pc of the Sun, Bingham (1967) concludes from the distortion of the interstellar magnetic field that the principal ridge of the North Polar Spur lies 100 pc from the Sun. Seymour (1969) concludes from a similar analysis that the distance is between 0 and 110 pc. Mathewson (1970) suggests 50–200 pc as the distance to the dust associated with the spur, which is presumably responsible for the observed starlight polarization. The assumption made in all the above analyses is that Loop I is a more or less hollow spherical object seen best along its edges, and that the interstellar polarization data are most strongly affected for lines of sight which lie nearly tangent to the spherical shell. Haslam *et al.* (1971) obtain a distance to the tangent point somewhere between 50 and 100 pc, and a shell radius of 85–170 pc. They place the distance from the Sun to the center of Loop I in the range 100–200 pc. On the other hand, Hughes *et al.* (1971) have compared the H I absorption velocities observed in the spectra of extragalactic radio sources in the direction of Loop II (the Cetus Arc) with velocities obtained from optical absorption lines in the spectra of stars with known distances in the neighborhood of the loop; they conclude that the distance to the center of the loop is < 170 pc; hence, its radius is < 120 pc.

We should also point out that there is considerable structure in the radio continuum from the loops. The width of the loops (distance between half power points) is around 10–15°. There are sharp outer gradients (Haslam *et al.*, 1964) as well as steps still unresolved with a 20′ beam width (Holden, 1969). As shown by Bingham (1967) the magnetic field lines are probably converging at low latitudes for Loop I.

The loops are just about numerous enough to account for the bulk of the non-thermal background radiation observed at low galactic latitudes (cf. Berkhuijsen, 1971).

Finally, the North Polar Spur (Loop I) has been observed also in the soft X-ray region (Bunner *et al.*, 1972). There is emission of soft X-rays in the energy range 160 eV $< E <$ 1000 eV from the vicinity of Loop I. One can see a gradual decrease of the $E <$ 284 eV intensity with galactic latitude decreasing towards the plane, while the 500 eV $< E <$ 1000 eV intensity remains approximately constant; the observers attribute this effect to the enhanced X-ray absorption nearer the plane. The intensity observed at 260 eV could have been attenuated by a factor of five. They estimate a radius of the spherical shell of ~ 100 pc. The intensities observed in their channels are hard to interpret if the unresolved spectrum were dominated by any X-ray emission lines, so they regard it as a continuum.

III. The Loops as Fossil Strömgren Spheres

The realization that the Gum Nebula was probably produced by the explosion that left behind the Vela X pulsar and the radio remnant (See Brandt *et al.*, 1971), raises the question as to whether the Gum Nebula is an isolated phenomenon. It is plain (Kafatos and Morrison, 1971) that objects similar to the Gum Nebula would in general be hard to detect. The Gum Nebula itself is made easy to detect only by a combination of fortunate circumstances; objects like the Gum Nebula are hard to find from far away. If the loops are in fact similar to the Gum Nebula, but much older, the implication is that they are numerous in the galaxy, although hard to notice once farther away than a few hundred parsecs (the distant loops eventually merge into the diffuse non-thermal radio background).

The picture adopted here is as follows (see also Brandt and Maran, 1972): A giant H II region is produced in a particular supernova explosion (it is not expected that all supernova explosions give rise to fossil Strömgren spheres). The temperature of the fossil Strömgren sphere (FSS) is initially $> 10^5$ °K. A supernova outburst that releases some 10^{62} ionizing photons will form such a fully ionized region ($R \sim 100$ pc if $n_0 \sim 1$ cm^{-3}, where n_0 is the ambient gas density); if the predominant radiation is hard ultraviolet, $h\nu < 100$ eV, the boundary is sharp and a "classical" Strömgren sphere is formed, although it is "fossil" in the sense that the ionizing agent ceases to exist (Morrison and Sartori, 1969; Kafatos and Morrison, 1971; Kafatos, 1971). If, on the other hand, appreciable amounts of soft X-ray photons are emitted as well ($h\nu > 100$ eV), a partially ionized shell will be formed outside the fully ionized zone; temperatures $T > 10^4$ °K are expected in the shell if the ionized fraction y (where $y = n_e/n_0$) is > 0.04 (McCray and Schwarz, 1971; Schwarz, 1973). (We should point out, however, that other theories have been advanced for the Gum Nebula. Although in those theories the ionization takes place over a period of $\sim 10^4$ years, instead of at light speed (cf. Tucker, 1971), the end result resembles that from the sudden photoionizing flash, as long as one is concerned only with time-scales larger than 10^4 years).

At first we have the true "Gum Nebula stage" (lasting a few $\times 10^4$ years). The central region is still hot and ionized (this region requires $2 \times 10^4/n_0$ years to cool from 10^5 °K down to 10^4 °K; n_0 is less than 1, except perhaps very near the galactic plane). The partially ionized outer shell remains at $\sim 10^4$ °K. In the radio band the whole region emits primarily thermal radiation. We see no way to find it except through the *absence* of 21-cm absorption from the vicinity of the supernova, or through a few unusually strong optical forbidden lines (Kafatos and Morrison, 1971).

The edge of the FSS is hotter than its surroundings; therefore a hydromagnetic shock will originate at the edge and travel outward, compressing the adjacent interstellar magnetic field and the cosmic-ray gas. Eventually we enter the second stage, which is the "Loop stage".

The edge of the region is made visible in radio continuum through an enhancement of the normal synchrotron radiation of the compressed cosmic-ray electrons in the compressed interstellar magnetic field. This mechanism is essentially that which van der Laan (1962) used to explain the synchrotron emission from some old supernova remnants. Here, however, the expansion arises in pre-existing interstellar gas because of a thermal pressure gradient, not from an ejected shell of stellar material. The loop radiation will stand out above background until the shock velocity becomes comparable to the turbulent velocities prevalent in the interstellar medium (1–5 km/s). The shock velocity will be somewhat greater than the thermal velocity, the latter being 10–55 km/s initially (for temperatures in the range $10^4 - 3 \times 10^5$ °K). Cox (1972) has considered the structure of a shock-wave of shock-velocity 100 km/s in the interstellar medium. Using his analysis we find that for a maximum temperature of $\sim 10^5$ °K in the shock region, the shock velocity is ~ 75 km/s. Initial shock velocities of this order of magnitude are expected. Also Cox shows that if the component of the magnetic field to the shock velocity is small (say 10^{-7} G) then the shock thickness is less than $\sim 10^{17}$ cm, while if it is of the order that one expects in interstellar space ($\sim 3 \times 10^{-6}$ G) the thickness is larger than 10^{18} cm. Therefore a shock thickness of at least a parsec is theoretically not unreasonable, and is suggested by the observations. Note that the sharp steps seen in intensity (Holden, 1969), which are probably smaller than 0.5 pc, might be regions where the magnetic field is almost parallel to the shock velocity.

A lower limit to the age of the loops is provided by the following argument: the age should be larger than the shock traversal time, $t_s = x/V_s$, where x is the shock thickness and V_s the shock velocity; if $x > 1$ pc, and $V_s \sim 50$ km/s, then the loops are at least 10^4 years old. They are probably older by at least an order of magnitude than this lower limit (compare results in Table 1). If no appreciable partially-ionized transition region exists, the fully ionized region cools to 10^3 °K after about $6 \times 10^4/n_0$ years. On the other hand, the partially-ionized shell would remain at $\sim 10^4$ °K even after 10^6 years (Schwarz, 1972). Therefore, if the age of the loops is a few $\times 10^5$ years, it follows that interstellar densities around 0.1 cm^{-3} or less are needed in the fully ionized models (UV models of initial ionization). This problem is not encountered by the models with partially-ionized shell (soft X-ray models).

Table 1

Assumed loop radius (in pc)	Radius of region containing 4 loops (in pc)	Total number in galaxy	Mean lifetime of loops in years for frequency of producing events in (year)$^{-1}$		
			1/30	1/100	1/300
20	60	7×10^5	2×10^7	7×10^7	2×10^8
50	150	4.4×10^4	1.3×10^6	4.4×10^6	1.3×10^7
85	250	9.6×10^3	2.9×10^5	9.6×10^5	2.9×10^6
170	500	1.2×10^3	3.6×10^4	1.2×10^5	3.6×10^5

To continue our analysis, we need some rough estimates of the total number of the loops in the galaxy, their lifetimes as well as their sizes. We assume that all four loops are of roughly the same size; this is the simplest assumption that can be made in the fact of the unknown sizes and distances of the loops. Different values are assumed for the size of the loops. These are listed in the first column of Table 1. The 20 pc radius is expected for a rather old supernova remnant of the type of the Cygnus Loop: it is probably also a lower limit for a FSS. (The small radius would imply a total energy in the photoionizing burst of $< 10^{50}$ erg (if $n_0 \sim 1$/cc), a rather weak SN explosion.) The last two radii are the limits of the region in which the radius of Loop I is expected to lie, according to Haslam *et al.* (1971). In the same table we present the size of the region inside which the four loops exist for a given radius, their total number in the galaxy, and the corresponding mean lifetimes, assuming that the events giving rise to them occur every 30, 100 and 300 years in the galaxy; the effective volume of the galaxy is assumed to have a radius of 10 kpc and a thickness of 500 pc. This value of the thickness refers to the thickness of the loop distribution; the thickness of the non-thermal radio-emitting disk may be even higher (see Baldwin, 1967; Bridle and Venugopal, 1969). According to Ilovaisky and Lequeux (1972) the non-thermal radio background near the plane may be due to very old supernova remnants. However, the z-distribution of supernova remnants is considerably narrower than that of the radio emission, which suggests that the galactic emission is not made merely of superposed supernoval remnants. A two-disk model of the galaxy provides a good fit to the radio background (Ilovaisky and Lequeux, 1972); the inner disk has full thickness 500 pc while the outer one has 2000 pc; their radial extent is ~ 10 kpc. We assume here that the thickness of the loop distribution is equal to the thickness of the inner disk.

We see that the loops probably have mean lifetimes exceeding 10^5 years; since the Gum Nebula is not older than 2×10^4 years, the loops represent a class of objects considerably older than the Gum Nebula. Their long lifetimes may explain the absence of radio remnants near their centers; the radio remnant of a supernova explosion may not last more than 10^5 years (Milne, 1970); the closeness of the Lupus Loop to the center of Loop I may thus be a coincidence.

A. The Radio Emission of the Loops

We now turn to the mechanism responsible for the radio loops. In the van der Laan compression mechanism the volume emissivity (in the one-dimensional case) is given by:

$$\varepsilon = \varepsilon_0 (K/K_0)(B/B_0)^{\alpha+1}\,\eta^{\alpha+1/2}\, f(\eta, \alpha) \tag{1}$$

in $W - m^{-3} - (c/s)^{-1}$, where the index "0" refers to the undisturbed medium, the electrons have the power law spectrum $N(E)\,dE = K_0 E^{-m}\,dE$ in the undisturbed medium, $\alpha = (m-1)/2$ and η is the compression ratio ($\eta = \varrho/\varrho_0$) behind the shock wave; $f(\eta, \alpha)$ is a function of η and α of the order of 1; in the one dimensional case $B/B_0 = \eta$ and $K/K_0 = \eta$; setting $f = 1$, Eq. (1) becomes:

$$\varepsilon = \varepsilon_0\, \eta^{2\alpha + 5/2}\,. \tag{2}$$

The undisturbed medium volume emissivity ε_0 can be found once B_0, and the electron cosmic ray spectrum as well, are known. Then the contribution of a loop to the radio background may be found, if the compression η is estimated. This is uncertain, since the origin of the background is not itself well known; a substantial part of the background can come from the loops, or be due to supernova remnants, or arise in the general interstellar medium by the synchrotron process. To proceed certain assumptions have to be made.

We assume that the background near the direction to Loop I primarily arises in the interstellar medium from the synchrotron emission of cosmic ray electrons spiraling in the galactic magnetic field. Then the ratio of specific intensities at the earth is:

$$I/I_0 \cong \varepsilon/\varepsilon_0\, R_{\mathrm{eff}}/d_{\mathrm{eff}} \tag{3}$$

where I_0 is the specific intensity received at the earth in the direction of Loop I but not containing it (background); d_{eff} is the effective size of the loop along the line sight. If the loop has a thickness of a few degrees the longest intercept of a line of sight through it is close to the length of the radius; taking I/I_0 a few (say 2), $R_{\mathrm{eff}} \approx R/2$, and taking into account the two-disk model, by combining Eq. (2) and (3) the compression η may be found. A correction has to be applied in the 3-dimensional case as discussed by van der Laan; the approximate values of η are 6, 5, 4, 3.5 for R equal to 20, 50, 85, 170 pc respectively 1). We stress again that the above analysis assumes that a substantial part of the nonthermal radio background arises in the interstellar medium via the synchrotron process. The values of η obtained above indicate that only mild compressions are needed to account for the radio brightness of the loops.

We may now easily find the total contribution of the loops to the radio background, and this is:

$$P_l = \varepsilon \cdot 4\pi R^2 N x \tag{4}$$

(Watt H_z^{-1}); x is the thickness; R the radius of a loop. Equation (4) implicitly assumes that all loops have more or less the same brightness as well as size. Otherwise a distribution function should be used; this of course is unknown. Moreover, N is subject to the uncertainties discussed above. Nevertheless (4) is useful for fough, order of magnitude calculations; the thickness of the shell x is less than $R/10$ – most likely between $R/10$ and $R/20$ – (because in the 3-dimensional case $\eta - R/3x$); this agrees with an apparent thickness of a few degrees (Berkhuijsen *et al.*, 1970). The contribution of the loops to the background found by using Eq. (4) is the larger the smaller the radius; in fact, for the smallest radius (20 pc) the radio background is mostly due to the summed loops, which may even be brighter than the measured total background. This is another argument against the smallest size. On the other hand, even for the largest radius (170 pc), the contribution is at least 25%. It seems reasonable therefore that the summed loops contribute a major part of the radio background; and they may account for most of the inner disk radiation. This agrees with Berkhuijsen's (1971) results.

One may ask what the thermal radiation from the loops is: it is an order of magnitude less than the synchrotron emission, even when T is as high as 10^4 °K. Right after loop formation the thermal radiation is dominant, for the edge has not yet moved very much; at this stage the region cannot be observed, because the background and any chance strong nearby sources will mask it (as is the case with the Gum Nebula). Typical radio fluxes of the order of 10 f.u. are expected from a segment of angular radius of 1°.

B. The X-ray *Emission of the Loops*

The recently discovered soft X-rays (Bunner *et al.*, 1972) from the North Polar Spur are harder to account for. As pointed out by Ilovaisky and Bowyer (1971), if the loops are well evolved supernova remnants, then they are not expected to be soft X-ray emitters; this is so because for loops as large as indicated ($R \approx 100$ pc), the shock temperature is well below what is needed to

---

1) Such compressions are not unreasonable theoretically, and in fact they are expected for shock velocities in the range 10–50 km/s, interstellar densities in $0.1 - 1\ \mathrm{cm}^{-3}$ and magnetic fields around 3×10^{-6} G.

1973A&A....26...71K

give rise to soft X-rays (while Vela X and the Cygnus Loop do emit in soft X-rays because their diameters are so much smaller). The intensities observed indicate that temperatures higher than 10^6 °K are needed, if the emission is by bremsstrahlung. Such temperatures are too high for the edge of a FSS. According to our picture, therefore, bremsstrahlung is ruled out. On the other hand, it is possible to interpret the soft X-rays as non-thermal synchrotron radiation.

We estimate the expected intensity of X-rays, rather than merely the contrast with background, because of the heavy absorption indicated in the directions near the galactic plane, where the Spur becomes invisible at 260 eV (Brunner *et al.*, 1972). We take the electron flux used by Goldstein *et al.* (1970) in their fit to the radio flux from 1 to 10^3 MHz. This differential spectrum falls like $E^{2.5}$, with E the electron energy. Synchrotron X-rays, even in the several-fold enhanced field within the shock, require electron energies in the neighborhood of 10^4 GeV, from the relation $\gamma_{\text{elec}} \sim 10^8/\sqrt{B_\perp}$ (where $B_\perp$ is the magnetic field component perpendicular to the electron velocity, measured in microgauss). At such high energies there are both experimental and theoretical arguments for a faster fall-off in electron flux with energy than that used for radio emission studies. We assume that the electron distribution *steepens* by one unit in the exponent at an energy of 300 GeV. The electron radiative lifetime is given roughly by the relation $2 \times 10^5/(B_1)^{3/2}$ yr; this lifetime implies a fall-off in background electrons. (The lifetime within the enhanced region is controlled by transport processes rather than by energy loss.) Fitting the Goldstein *et al.* curve at 10 GeV, (using a field of 5 microgauss), extrapolating to the match point at 300 GeV, and choosing beyond that the electron spectrum $d\phi \alpha\, dE/E^{3.5}$, we obtain

$$d\phi = 2.5 \cdot 10^{23}\, dE/(E_{\text{eV}})^{3.5} \text{ electrons/cm}^2 - \text{s} - \text{sr} - \text{eV}\,. \tag{5}$$

Converting to density from flux, and changing units, we compute the background electron emissivity to be

$$\varepsilon_0 = 8 \cdot 10^{-19}/(h\nu(\text{eV}))^{2\frac{1}{4}} \quad \text{eV/cc} - \text{s} \tag{6}$$

(cf. formula 5.47 in Ginzburg and Syrovatski (1965)). The shell enhancement is given by our Eq. (1) and (2). But the index m is now 3.5. The enhancement factor $\eta^{m+3/2}$ can be chosen for an intermediate radius estimate, say $R_{\text{eff}} \sim 50$ pc, and yields an intensity:

$$I = \varepsilon_0 R_{\text{eff}} \eta^5/4\pi \cong 0.11 \quad \text{ph/cm}^2 - \text{s} - \text{sr} - \text{eV}\,, \qquad \text{with} \quad \eta = 5$$

to be compared with the experimental intensity reported, $I(260 \text{ eV}) = 0.3$ ph/cm^2 – s – sr – eV.

The steep extrapolation and the dependence of this prediction on the enhancement factor, and hence on the geometry of the shock, do not appear to justify a closer comparison. It seems plain that plausible conditions produce a satisfactory account of the observed soft X-rays on our model.

Table 2

Assumed loop radius (in pc)	Maximum kinetic energy in a loop (erg)	Maximum initial energy[a]) (erg)	Ratio of kinetic energy to initial energy (%)
20	1.5×10^{49}	1.5×10^{50}	10
50	10^{50}	2×10^{51}	5
85	2.5×10^{50}	10^{52}	3
170	10^{51}	10^{53}	1

[a]) Assuming that the interstellar gas density is at most 1 cm^{-3} and that the average photon energy emitted in the ionizing burst is 100 eV.

Both at radio frequency and in soft X-rays the loops stand out against a continuous galactic background with similar $(10^2 - 10^3)$ emissivity contrast. This gains a very natural explanation if both radiations in fact arise out of a common local enhancement of the widely distributed sources of the general background. The circumstance lends support to the present theory, for there seems to be little reason to expect such a relationship to hold across so much of the electromagnetic spectrum unless the background and loops tap in a sense some common store of energy.

C. The Visible Filaments

In the model presented here the optical filaments of the loops are naturally accounted for in terms of the thermal instability process (McCray *et al.*, 1972). These filaments are 13 times less bright than the Cygnus Loop filaments. Specific intensities of the order of $10^{-5} - 10^{-6}$ erg/cm^2 – s – sr would imply $T > 10^4$ °K and densities in the range $0.2 - 2$ cm^{-3} for characteristic sizes in the range $0.1 - 1$ pc. On the other hand, from the upper limit on the proper motion of the filaments, velocities of expansion less than 100 km/s are implied.

The total energy content of a loop can also be estimated. Velocities of expansion (Fejes, 1971 a and b) for Loop IV in the range 30–40 km/s are indicated. From the H I observations of Berkhuijsen *et al.* (1970) the surface density of 2×10^{20} atom/cm^2 implies masses in the shell of the order of $10^4 M_\odot$, or $5 \times 10^4 M_\odot$, for $R = 85$ pc, or 170 pc (Haslam *et al.*, 1971). The surface density of the neutral hydrogen shell is comparable to the surface density of the shell emitting the soft X-rays (Bunner *et al.*, 1972) and this implies that the two regions have comparable sizes. If the velocity of expansion is less than 50 km/s the kinetic energy content is tabulated in Column 2 of Table 2 (upper limits). Assuming that the density is at most 1 cm^{-3} and that the average photon energy emitted initially in the ionizing burst is ≈ 100 eV, the upper limit to the total initial energy emitted in the ionizing burst is given in Column 3 of Table 2. Column 4 gives the ratio of the present energy of expansion to the total initial energy (%).

Finally, the total energy involved over the lifetime of a loop in radio and X-ray emission is less than 1% of the total energy in the initial burst for all four choices of radii.

It is seen that the kinetic energy, in general, is a few percent of the total energy emitted initially, while the energies involved in the radio and soft X-ray emission are negligible. Most of the energy emitted in the explosion ionizes the surrounding gas or is re-emitted in the hard ultraviolet, which again ionizes the gas further out, as the region cools.

It is interesting to speculate on spatial distribution of the loops. This would help decide whether they belong to Population I or II and presumably say something about their origin. The sample of four loops is obviously too small for any meaningful conclusions to be drawn; note however that if $R \sim 170$ pc the centers of two loops (III and IV) are located 100 pc above the galactic plane.

If the loops are indeed circular it is difficult to understand how they can have radii in the range 100–200 pc. Since the thickness between half-density points is 220 pc (Kerr and Westerhout, 1965), the effects of the drop-off of the interstellar gas density with height above the plane, should be noticeable as radii varying with distance from the plane.

It seems to us that just about any theory of the loops leads to this puzzle *if* the thickness of the galaxy is as quoted above, and *if* the loops are as large as believed to be. Perspective effects cannot be expected to provide a solution because all four loops, not just one of them, are quite circular. It may be that the loops are not really as circular as they are said to be, or that the scale height of galactic hydrogen is larger by a factor of a few – at least in the solar neighborhood – than the value now accepted. We feel that there are quite strong arguments against small sizes unless a special theory is evoked, and therefore that the problem of strict circularity – which is strangest if the sizes are large – is indeed a very real one, for the radius reached by almost any propagation mechanism would be expected to vary with ambient gas density. Only the "rainbow"-like mechanisms might avoid this argument, but see Manchester (1972).

IV. Conclusions

The loops have been interpreted as being old fossil Strömgren spheres, similar to the Gum Nebula, of the order of 1–200 pc diameter. The radio continuum and the soft X-ray emission both can arise from the synchroton interaction of galactic cosmic ray electrons with the strengthened interstellar magnetic field in the bounding region of shock compression. The total number of the loops in the galaxy as well as their total contribution to the non-thermal radio background have been estimated; these depend on what the size of the loops really is. The loops are probably as large (ca. 100 pc) as indicated by the observations. The remaining knottiest problem is their accurate circularity. If the loops are indeed as circular as they are believed to be and as large as 100 pc in radius or more, then the density of the interstellar gas, at least in the galactic neighborhood of the sun, has to remain roughly constant for a couple of hundred parsecs above the plane.

We feel that before more theories for the loops are produced, a few experimental assurances are required: i) we need a firm radio spectrum for all the loops, as well as the soft X-ray spectrum of Loop I. ii) The other loops should be examined for soft X-ray emission. iii) The reliability of the conventional single scale-height model of the gas in the neighborhood of the sun should be confirmed.

Acknowledgements. We have benefited from helpful discussions with R. A. McCray and W. H. Tucker.

References

Baldwin, J. E. 1967, in *Radio Astronomy and the Galactic System;* IAU Symp. No. 31, 337, Academic Press,
Berkhuijsen, E. M. 1971, *Astron. & Astrophys.* **14**, 359.
Berkhuijsen, E. M., Haslam, C. G. T., Salter, C. J. 1970, *Nature* **225**, 364.
Bingham, R. G. 1967. *Monthly Notices Roy. Astron. Soc.* **137**, 157.
Brandt, J. C., Maran, S. P. 1972, *Nature* Feb.
Brandt, J. C., Stecher, T. P., Crawford, D. L., Maran, S. P. 1971, *Astrophys. J. Letters* **163**, *L* 99.
Bridle, A. J., Venugopal, V. R. 1969, *Nature* **224**, 545.
Brown, R. Handbury, Davies, R. D., Hazard, C. 1960, *Observatory* **80**, 191.
Bunner, A. N., Coleman, P. L., Kraushaar, W. L., McCammon, D. 1972, *Astrophys. J.* **172**, L 67.
Caswell, J. L., Crowther, J. H., Holden, D. J. 1967, *Mem. Roy. Astron. Soc.* **72**, 1.
Cox, D. P. 1972, *Astrophys. J.* **178**, 159.
Downes, D. 1970, Ph. D. Thesis, Harvard University.
Elliott, K. H., Meaburn, J. 1970, *Astrophys. Space Sci.* **6**, 252.
Fejes, I. 1971a, *Astron. & Astrophys.* **11**, 163.
Fejes, I. 1971b, *Astron & Astrophys.* **15**, 419.
Ginzburg, V. I., Syrovatskii, S. I. 1965, Ann. Res. *Astron & Astrophys.* **3**, 297.
Goldstein, M. L., Ramaty, R., Fisk, L. A. 1970, *Phys. Rev. Letters* **24**, 1193.
Haslam, C. G. T., Large, M. I., Quigley, M. J. S. 1964, *Monthly Notices Roy. Astron. Soc.* **127**, 237.
Haslam, C. G. T., Kahn, F. D., Meaburn, J. 1971, *Astron & Astrophys.* **12**, 388.
Holden, D. J. 1969, *Monthly Notices Roy. Astron. Soc.* **145**, 67.
Hughes, M. P., Thompson, A. R., Colvin, R. S. 1971, *Astrophys. J. Suppl.* No. 200, **23**, 323.
Ilovaisky, S. A., Bowyer, S. 1971, *Nature* **223**, 469.
Ilovaisky, S. A., Lequeux, J. 1972, to be published, *Astron. & Astrophys.*
Kafatos, M. C., Morrison, P. 1971, *Astrophys. J.* **168**, 195.
Kafatos, M. C. 1971, in *Gum Nebula and Related Problems*, Edit. S. P. Maran, J. C. Brandt and T. P. Stecher, NASA X-683-71-375, p. 110.

Large, M. I., Quigley, M. J. S., Haslam, C. G. T. 1962, *Monthly Notices Roy. Astron. Soc.* **124**, 142.
Katgert, P., Oort, J. H. 1967, *Bull. Astron. Inst. Neth.* **19**, 239.
Kerr, F. J., Westerhout, G. 1965, in *Stars and Stellar Systems*, Edit. by A. Blaauw and M. Schmidt, Vol. V, 1967, University of Chicago Press.
Manchester, R. M. 1972, *Astrophys. J.* **172**, 43.
Mathewson, D. S. 1968, *Astrophys. J. Letters* **153**, L 47.
Mathewson, D. S. 1970, *Mem. Roy. Astron. Soc.* **74**, 139.
McCray, R. A., Schwarz, J. 1971, in *Gum Nebula and Related Problems*, Edit. S. P. Maran, J. C. Brandt and T. P. Stecher, NASA X-683-71-375, p. 60.
McCray, R. A., Stein, F. R., Schwarz, J. 1972, *Astrophys. J. Letters* **177**, L75.
Meyer, P. 1969, *Ann. Rev. Astron. & Astrophys.* **7**, 1.
Milne, D. K. 1970, *Australian J. Phys.* **23**, 425.
Morrison, P., Sartori, L. 1969, *Astrophys. J.* **158**, 541.
Parker, E. N. 1965, *Astrophys. J.* **142**, 584.
Ramaty, R., Lingenfelter, R. E. 1971, *Phys. Rev. Letters* **27**, 1309.
Salter, C. J. 1970, Ph. D. Thesis, Manchester University.
Schwarz, J. 1973, submitted to *Astrophys. J.*
Seymour, P. A. H. 1969, *Monthly Notices Roy. Astron. Soc.* **142**, 33.
Spoelstra, T. A. Th. 1971, *Astron. & Astrophys.* **3**, 237.
Tucker, W. H. 1971, *Astrophys. J. Letters* **167**, L 85.
van der Laan, H. 1962, *Monthly Notices Roy. Astron. Soc.* **124**, 125.
Zuzak, W. W. 1971, *Astron & Astrophys.* **15**, 95.

M. C. Kafatos
Joint Institute for Laboratory Astrophysics
University of Colorado
Boulder, Colorado 80302, USA

P. Morrison
Room 6–308
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139, USA