GIANT EXPLOSION AT THE GALACTIC CENTER AND HUge ShOCKED Shells IN THE HALO

Yoshiaki SOFUE
Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181
E-mail: sofue@sof.mtk.ioa.s.u-tokyo.ac.jp
(To appear in Ap.J. Letter)

Abstract
We simulate the propagation of a shock front through the galactic halo induced by an explosion and/or a starburst at the galactic center. A huge dumbbell (Ω)-shaped shock front produced by an explosion of energy $3 \times 10^{56}$ ergs about fifteen million years ago can mimic the radio and X-ray North Polar Spur as well the southern large X-ray spur. The post-shock high-temperature gas in the corona will explain the observed X-ray bulge around the galactic center.

Key words: Galaxy: center – Galaxy: halo – Radio continuum: general – Shock wave – X-rays: general

I. GIANT EXPLOSION MODEL
It is known that our Galactic Center has experienced various explosive events (Oort 1977), and a number of expanding shells and rings have been observed, associated with radio, X-ray and gaseous ejection of various scales (Sofue 1989). In this letter we point out that the large-scale radio loops and X-ray diffuse emission around the galactic center can be explained by a giant explosion model.

The propagation of a shock front through the galactic halo induced by a point energy injection at the center can be numerically simulated by applying the self-similarity method (Sakashita 1971; Sofue 1984). We assume an unperturbed density distribution of gas in the Galaxy as the following:

$$\rho = \rho_0 e^{-\{(\varpi/\varpi_0)^2 + (z/z_0)^2\}} + \rho_H e^{-z/z_H} + \rho_{IG},$$

(1)

where $\varpi$ and $z$ are the distances from the rotation axis and the galactic plane, respectively. The first term represents the gas disk, and the constants are taken to be $\rho_0 = 3$ H cm$^{-3}$, $\varpi_0 = 7$ kpc, and $z_0 = 100$ pc. The second term is a thick disk (or a halo) of atomic and molecular hydrogen, which is indeed observed in several edge-on galaxies like NGC 891, and we take $\rho_H = 0.03$ H cm$^{-3}$ and $z_H = 1$ kpc. The third term is the intergalactic gas with a constant density of $\rho_{IG} = 10^{-6}$ H cm$^{-3}$. The formula gives a local hydrogen density of 1 H cm$^{-3}$ in the solar vicinity.

The shock propagation has been calculated according to the method described by Sofue (1984). The result for an explosion energy of $E = 3 \times 10^{56}$ is shown in Fig. 1 and Fig. 2, where the tangential part of the shock front projected on the sky is superposed on the observed X-ray maps and on the radio map. The shock front at $b \sim 30^\circ$ reaches a radius of $r = 5$ kpc at $t = 1.5 \times 10^7$ years since the explosion, and the expansion velocity is $v \sim 200$ km s$^{-1}$. The calculated shock speed is higher in the polar direction than in the disk, which yields the Ω-shaped front. The shock wave heats the halo gas up to $\sim 10^{6.5}$ K, and a high-temperature corona remains in the post shock, which will be
observed as an X-ray bulge. The emission measure toward the shock front at \( b \sim 30^\circ \) is estimated to be \( 0.03 \, \text{cm}^{-6} \, \text{pc} \). The emission measure along the line tangential to the front is approximately proportional to the mass plowed by the front from the galactic center, therefore proportional to cosec \( b \), and is indeed observed in the M-band intensity variation along the NPS (Fig. 3). The cooling time of the hot gas is \( \sim 10^9 \) years, and so, the halo gas is almost adiabatic.

II. RADIO AND X-RAY FEATURES

The North Polar Spur (NPS) is a giant arc on the sky (Fig. 2), and has been studied on the assumption that it may be a local supernova remnant (SNR), that had been proposed three decades ago based on the earliest low-resolution data (Berkhuijsen et al. 1971; Spoelstra 1971; Egger 1993). The SNR hypothesis has been criticized by Sofue et al. (1974), and some authors have suggested that it could be a galactic scale phenomenon such as a galactic helical magnetic field (Mathewson et al. 1968), or a magnetic inflation from the galactic disk (Sofue 1973, 1976), and a giant shock hypothesis has been proposed by Sofue (1977, 1984). We here revisit the NPS by applying an advanced data processing technique to the modern radio data (Haslam et al. 1982), and combine them with the X-ray all-sky survey.

Fig. 2 shows a new radio view of the NPS, which has been obtained by applying the background-filtering technique (Sofue and Reich 1979) to the 408 MHz whole-sky map (Haslam et al. 1982). The NPS comprises a well-defined shock front at \( l \sim 30^\circ \). The radio ridge becomes sharper and narrower toward the galactic plane (Sofue and Reich 1979), and the brightness attains the maximum at \( b \sim 10^\circ \). On this new radio view, the NPS and the major arcs along Loop IV (Berkhuijsen et al. 1971) can be naturally traced as one object, composing a giant Omega anchored with its both roots to the galactic plane at \( l \sim 20^\circ \) and \( l \sim 340^\circ \). Negative-latitude spurs are seen at \( l \sim 340^\circ \) to \( 320^\circ \), \( b \sim -10^\circ \) to \(-30^\circ \) and at \( l \sim 20^\circ \), \( b \sim -2^\circ \) to \(-40^\circ \), though not clear. We stress that the NPS can be approximately fitted by the calculated shock front after \( t \sim 1.5 \times 10^7 \).

Fig. 1 shows X-ray maps in the M (0.6 - 1.1 keV) and C (0.6 - 0.28 keV) bands (McCammon et al. 1983; McCammon and Sanders 1990). The M-band map shows a global enhancement around the Galactic Center due to a hot gas bulge (McCammon et al. 1983), which indicates that the local HI disk is transparent at \( b > \sim 10^\circ \). Enhancement along the NPS is evident in both bands. A southern X-ray spur is also visible, particularly in the HEAO M-band map (McCammon and Sanders 1990), emerging from \( (l, b) \sim (340^\circ, -10^\circ) \). All these features appear to be well fitted by the calculated shock front. The C-band map shows “polar caps” at high latitudes, which is also fitted by the calculated shock front. On the other hand, the C-band emission shows a wide absorption band along the galactic plane, and the C-band NPS is also absorbed below \( b = 60^\circ \), hardly visible below \( 30^\circ \).

Another remarkable feature in the M band is the sharp shadowing near the galactic plane due to the local HI layer and the Hydra ridge (Cleary et al. 1979). Fig. 3 shows the variation of X-ray intensities along the NPS, where the uniform background component has been subtracted and the values are normalized to unity at \( b = 60^\circ \). Observed HI column density within \(-70 \) to \(+90 \) km s\(^{-1}\) is also plotted (Cleary et al. 1979) together with that for a plane-parallel model HI layer. The M band emission increases toward the galactic plane, and appears to be strongly absorbed at \( b < 10^\circ \). This absorption feature shows an
excellent correlation with the increasing HI column density, and is naturally understood if the X-ray emitting region lies beyond the HI disk further than 100 pc/sin 10° ~ 600 pc.

Since the NPS at b > 60° is clearly visible in the I (0.8 - 1.5 keV) band, the temperature would be much higher than 10^6 K. Although a multi-temperature model may be required for a detailed fitting, we here simply assume that the temperature is about 10^{6.5} K. Then, we can estimate the intrinsic (non-absorbed) C-band intensity relative to the emission at b = 60°, which mimics the M-band distribution. However, the observed C-band intensity is strongly absorbed below b = 60° (Fig. 3), and the intensity at b = 30° is only 0.09 times that of thus expected intrinsic value. Using the C-band transmission diagram (Fig. 11 of McCammon et al 1983), we can estimate the corresponding HI mass to be 7 × 10^{20} H cm^{-2}, which is greater than the observed value (5 × 10^{20} H cm^{-3}). Hence, we may conclude that the X-rays at b ~ 30° originate beyond the hydrogen layer. As Fig. 3 indicates, the C-band emission is almost totally absorbed below b ~ 25°. All these facts are consistent with the idea that the NPS lies in the halo beyond the local disk.

According to the present model, the HI gas from the thick disk will be accumulated in front of the shocked shell. In the galactic plane it will make an expanding ring of a radius about 2.5 kpc, and appears to coincide with the 3-kpc expanding ring (Oort 1977). Above the galactic disk, an HI spur of intermediate velocity (V_{LSR} = 30 to 70 km s^{-1}) has been observed (Cleary et al 1979) at l ~ 30°, b ~ 10 to 30°. This velocity (~ 50 km s^{-1}) corresponds to a kinematic distance of 4.4 kpc and a galactocentric distance of 4.5 kpc. Conservation of the angular momentum due to the large expansion of the shell would result in a slower rotation at higher latitudes, where the accumulated HI will be visible at lower or even negative LSR velocities. In fact, a low-velocity HI spur is observed at b > 30°. On the other hand, it seems difficult to explain the apparent alignment of star-light polarization along the HI ridge (Mathewson 1968; Mathewson and Ford 1970), if they are physically associated. However, the physical alignment of star-light polarization along the shock-compressed shell is controversial (Spoestra 1971; Sofue et al. 1974).

### III. DISCUSSION

We have shown that many of the characteristics observed for the NPS and X-ray features around the Galactic Center can be explained if the Galaxy has experienced an active phase 1.5 × 10^7 years ago associated with an explosive energy release of some 10^{56} erg. As to the origin of the energy, we may consider (a) a giant explosion at the nucleus associated with the central massive black hole; and/or (b) a starburst which involved ~ 10^5 supernovae occurring in a relatively short period, say, in 10^6 yrs. These two models are, however, essentially the same as far as the formation of a shell of a large radius is concerned. In our Galactic Center, various explosive events have been reported, and a large number of expanding features are found, which could be the evidence for a past starburst (Sofue 1989). The total amount of energy is estimated to be about 10^{56-58} ergs (Oort 1977). Explosion and starburst are not rare events in external galaxies: radio shells of a few kpc scale in the halo are found in many spiral galaxies such as NGC 3079 (Duric et al 1983), NGC 4258 (van Albada 1980), and NGC 253 (Sofue 1984), which show an apparent similarity to the NPS.

The galactic-scale shock from the nuclear region will have an implication for the evolution of the Galaxy: The shock wave is an effective heating source of the hot corona.
It will contribute to a rapid circulation of heavy-elements from the inner disk to the entire Galaxy. Finally we point out that the NPS as well as the X-ray spurs and the hot bulge may become tools to probe the galactic halo and its intergalactic interface.

References
Berkhuijsen, E., Haslam, C. G. T., and Salter, C. J. 1971, AA 14, 252.
Cleary, M. N., Heiles, C., Haslam, C.G.T. 1979, AAS 36, 95.
Duric, N., Seaquist, E.R., Crane, P.C., Bignell, R.C., Davis, L.E., 1983, Ap.J.L, 273, L11.
Egger, R. 1993, Ph. D. Thesis, Univ. Munich, MPE Report No. 249.
Haslam, C.G.T., Salter, C.J., Stoffel, H., Wilson, W.E., 1982, AA Suppl. 47, 1.
McCammon, D. and Sanders, 1990, ARAA 28, 657.
McCammon, D., Burrows, D.N., Sanders.W. T., and Kraushaar, W. L. 1983, Ap.J. 269, 107.
Mathewson, D. S. 1968, Ap.J. 153, L47.
Mathewson, D. S., Ford, V. L. 1970, Mem. RAS, 74, 139.
Sofue Y, K.Hamajima, Fujimoto, M 1974, PASJ, 26, 399
Sofue, Y. 1973, PASJ, 25, 207.
Sofue, Y. 1976, AA, 48, 1.
Sofue Y 1977, AA 60, 327.
Sofue, Y. 1984, PASJ 36, 539.
Sofue Y, Reich, W. 1979, AA Suppl. 38, 251.
Sofue, Y. 1989, in The Center of the Galaxy (ed. M. Morris, Kluwer Academic Press, Dordrecht), p.213.
Spoelstra, T. A. T 1971, AA. 13, 273.
von Albada, R. D. 1980, AA Suppl. 39, 283.

Figure Captions

Fig. 1: Calculated shock front in the galactic halo at 1, 1.5 and 2 × 10^7 yr after an explosion and/or a starburst at the nucleus with a total energy of 3 × 10^{56} erg. The front is superposed on the M- and C-band X-ray maps (McCammon 1983).

Fig. 2a: The North Polar Spur at 408 MHz, showing a giant Ω over the Galactic Centre, as obtained by subtracting the background from the Bonn-Parkes all-sky survey (Haslam et al 1982) (top). The grid interval is 20° in (l, b) and (RA, Dec). The calculated shock front is superimposed on the sketch of the NPS (bottom).

Fig. 2b: The same as Fig. 2a but in a grey-scale representation.

Fig. 3: C and M-band X-ray intensities along NPS normalized to unity at b = 60° with the uniform background being subtracted. The observed HI column density and that for a plane-parallel HI layer are indicated.