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GIANT EXPLOSION AT THE GALACTIC CENTER AND HUGE SHOCKED SHELLS IN THE HALO

YOSHIAKI SOFUE
Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181, Japan
E-mail: sofue@mtk.ioa.s.u-tokyo.ac.jp
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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 3×10^{56} ergs about 15 million years ago can mimic the radio and X-ray North Polar Spur as well as 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.

Subject headings: Galaxy: center — Galaxy: halo — ISM: jets and outflows — radio continuum: general — shock waves — X-rays: galaxies

1. GIANT EXPLOSION MODEL

It has been suggested that our Galactic center has experienced explosive events, which are associated with radio, X-ray, and gaseous ejection features of various scales (e.g., Oort 1977; 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 Galactic center explosion.

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

$$\rho = \rho_0 e^{-\{(\varpi/\varpi_0)^2+(z/z_0)^2\}} + \rho_{\rm H} e^{-z/z_{\rm H}} + \rho_{\rm IG} , \qquad (1)$$

where ϖ 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 $\rho_{\rm H} = 0.03$ H cm^{-3} and $z_{\rm H} = 1$ kpc. The third term is the intergalactic gas with a constant density of $\rho_{\rm IG} = 10^{-6}$ H cm^{-3}. The formula gives a local hydrogen density of 1 H cm^{-3} in the solar vicinity.

The shock propagation for an explosion energy $E = 3 \times 10^{56}$ ergs has been calculated, and the resulting shock front is found to attain a dumbbell shape, when it is looked at from an infinite distance (see Sofue 1984). However, since the Sun is rather close to the shock front, the tangential part of the shell is closer than the geometrical shell center, and its projection on the sky suffers from a geometrical deformation. Figure 1 and Figure 2*a* show Aitoff and semi-Aitoff plots of the tangential part of the shock front at $t = 10$, 15, and 20 Myr superposed on the observed X-ray and radio maps, respectively.

The shock front observed at $b \sim 30°$ reaches a radius of $r = 5$ kpc at $t = 15$ Myr since the explosion, and the expansion velocity is $v \sim 200$ km s^{-1}, and the shock speed is much higher in the polar direction. 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 $b \sim 30°$ is estimated to be 0.03 cm^{-6} pc. The emission measure along a line tangential to the shock front is approximately proportional to the mass plowed by the front from the Galactic center, therefore proportional to cosec b, which is indeed observed in the M-band intensity variation (Fig. 3). The cooling time of the hot gas is $\sim 10^9$ years, and so, the halo gas is almost adiabatic.

2. RADIO AND X-RAY FEATURES

The north polar spur (NPS) is a giant arc on the sky (Fig. 2 [Pls. L11 and L12]), and has been studied on the assumption that it may be a local supernova remnant (SNR), which had been proposed three decades ago based on the earliest low-resolution data (Berkhuijsen, Haslam, & Salter 1971; Spoelstra 1971; Egger 1993). The SNR hypothesis has been criticized by Sofue, Hamajima, & Fujimoto (1974), and some authors have suggested that it might be a galactic scale magnetic phenomenon (Mathewson 1968; Sofue 1973, 1976). 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, and combine them with the X-ray all-sky survey.

Figures 2*a* and 2*b* show a new radio view of the NPS, which has been obtained by applying the background-filtering technique (Sofue & Reich 1979) to the 408 MHz whole-sky map (Haslam et al. 1982). The NPS comprises a well-defined shock front at $l \sim 30°$. The radio ridge becomes sharper and narrower toward the Galactic plane (Sofue & Reich 1979), and the brightness attains the maximum at $b \sim 10°$. 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 Ω shape anchored to the Galactic plane at $l \sim 20°$ and $\sim 340°$. Negative-latitude spurs are seen at $l \sim 340°$ to 320°, $b \sim -10°$ to $-30°$ and at $l \sim 20°$, $b \sim -2°$ to $-40°$, though not clear. We stress that the NPS can be approximately fitted by the calculated shock front after $t \sim 1.5 \times 10^7$.

Figure 1 shows X-ray maps in the M (0.6–1.1 keV) and C (0.16–0.28 keV) bands (McCammon et al. 1983; McCammon & Sanders 1990). The M-band map shows a global enhancement around the Galactic center due to a hot gas bulge

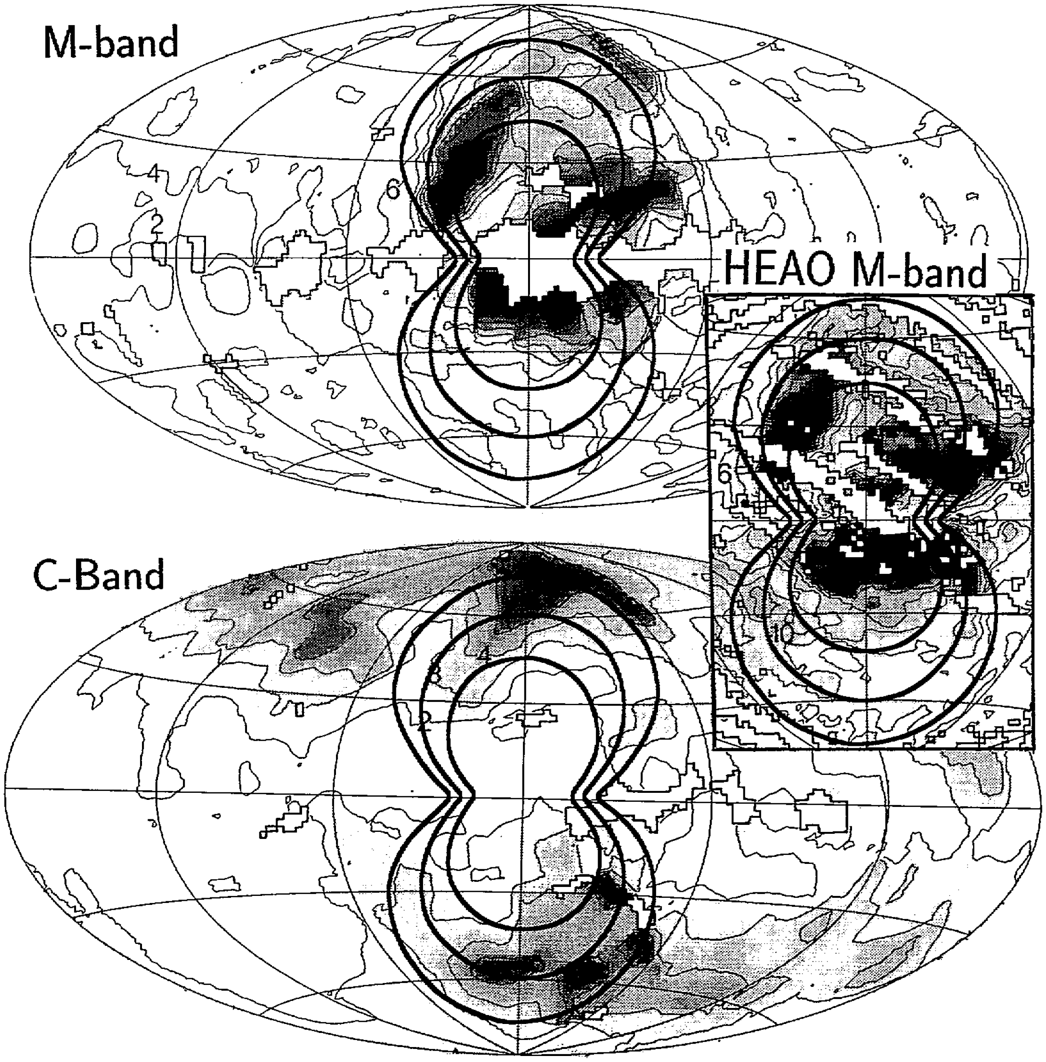

FIG. 1.—Calculated shock front in the Galactic halo at 1, 1.5, and 2×10^7 yr after an explosion and/or a starburst at the nucleus with a total energy of 3×10^{56} ergs. The front is superposed on the *M*- and *C*-band X-ray maps (McCammon et al. 1983).

(McCammon et al. 1983), which indicates that the local H I disk is transparent at $b > \sim 10°$. 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 & Sanders 1990), emerging from $(l, b) \sim (340°, -10°)$. 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 $b = 60°$, hardly visible below 30°.

The *M* band emission shows a remarkable shadowing near the Galactic plane due to the local H I layer (Cleary et al. 1979). Figure 3 shows the variation of X-ray intensities along the NPS, where the uniform background component has been subtracted and the values are normalized at $b = 60°$, and they are compared with the observed H I column density for $V_{\rm lsr} = -70$ to $+90$ km s^{-1} (Cleary, Heiles, & Haslam 1979) as well as with that for a plane-parallel model H I layer. The *M* band emission increases toward the Galactic plane, and is then strongly absorbed at $b < 10°$, showing an excellent correlation with the increasing H I column density. This can be naturally understood if the X-ray emitting region lies beyond the H I disk further than 100 pc/sin 0° ~ 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 multitemperature model may be required for a perfect fitting, we here simply assume that the temperature is about $10^{6.5}$ K for an approximate fit to the data: Then, the intrinsic (nonabsorbed) *C*-band intensity relative to the emission at $b = 60°$ can be calculated, and is found to mimic 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 the thus expected intrinsic value. Using the *C*-band transmission diagram (Fig. 11 of McCammon et al. 1983), we can estimate the corresponding H I 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 $b \sim 30°$ originate *beyond* the hydrogen layer. As Figure 3 indicates, the *C*-band emission is almost totally absorbed below $b \sim 25°$. All these facts are consistent with the idea that the NPS lies in the halo beyond the local disk.

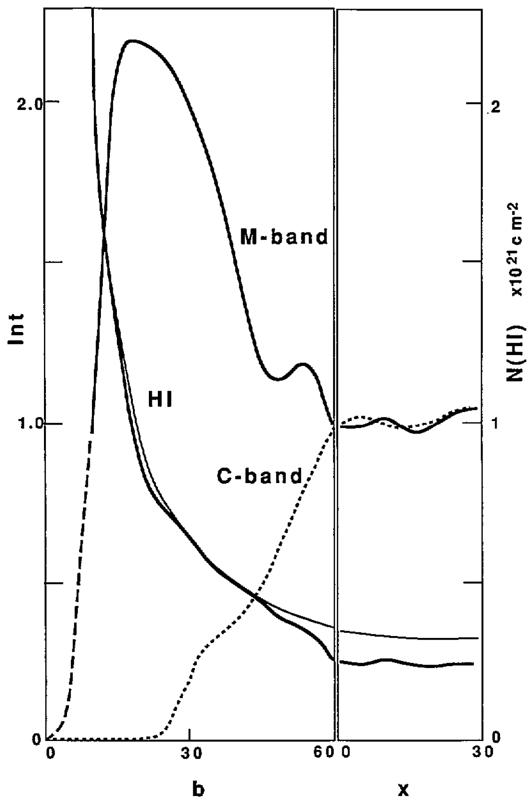

FIG. 3.—*C*- and *M*-band X-ray intensities along NPS normalized to $b = 60°$ with the uniform background being subtracted. The observed H I column density, and that for a plane-parallel H I layer are indicated.

According to the present model, the H I 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 of about 2.5 kpc, and appears to coincide with the 3 kpc expanding ring (Oort 1977). Above the galactic disk, an H I spur of intermediate velocity ($V_{LSR} = 30$ to 70 km s^{-1}) has been observed (Cleary et al. 1979) at $l \sim 30°$, $b \sim 10$ 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, and the accumulated H I will be visible at lower LSR velocities, which is indeed observed as an H I spur at $b > 30°$. It seems, however, difficult to explain the apparent alignment of starlight polarization along the H I ridge (Mathewson 1968; Mathewson & Ford 1970), although the physical alignment appears still controversial (Spoelstra 1971; Sofue et al. 1974).

3. DISCUSSION

We have shown that 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} ergs. 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 $\sim 10^5$ supernovae occurring in a relatively short period, say, in 10^6 yr. 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, a large number of expanding features are found, which could be the evidence for a past starburst and explosions, and the total amount of energy is estimated to be about 10^{56-58} ergs (Oort 1977; Sofue 1989).

Explosion and starburst are not rare events in external galaxies: radio shells of a few kpc scale are found in many spiral galaxies such as NGC 3079 (Duric et al. 1983) and NGC 4258 (van Albada 1980). The hard X-ray spurs observed in NGC 253 in the *Einstein* IPC image (Fabbiano 1988) suggests, besides the nucleus, a symmetrical double-lobed structure with a diameter of about 8′ (8 kpc for 3.5 Mpc distance), and this lobe structure has been more clearly observed in the *ROSAT* soft X-ray image (Pietsch, Trümper, & Zinnecker 1992).

We mention about the asymmetry of the NPS with respect to the rotation axis of the Galaxy and to the Galactic plane. Such an asymmetry may be not surprising in view of the fact that most shocked shells like supernova remnants and extragalactic shells as above show more or less strong asymmetry, probably due to the asymmetry in the distribution of ambient matter and/or in the condition during the initial explosion.

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.

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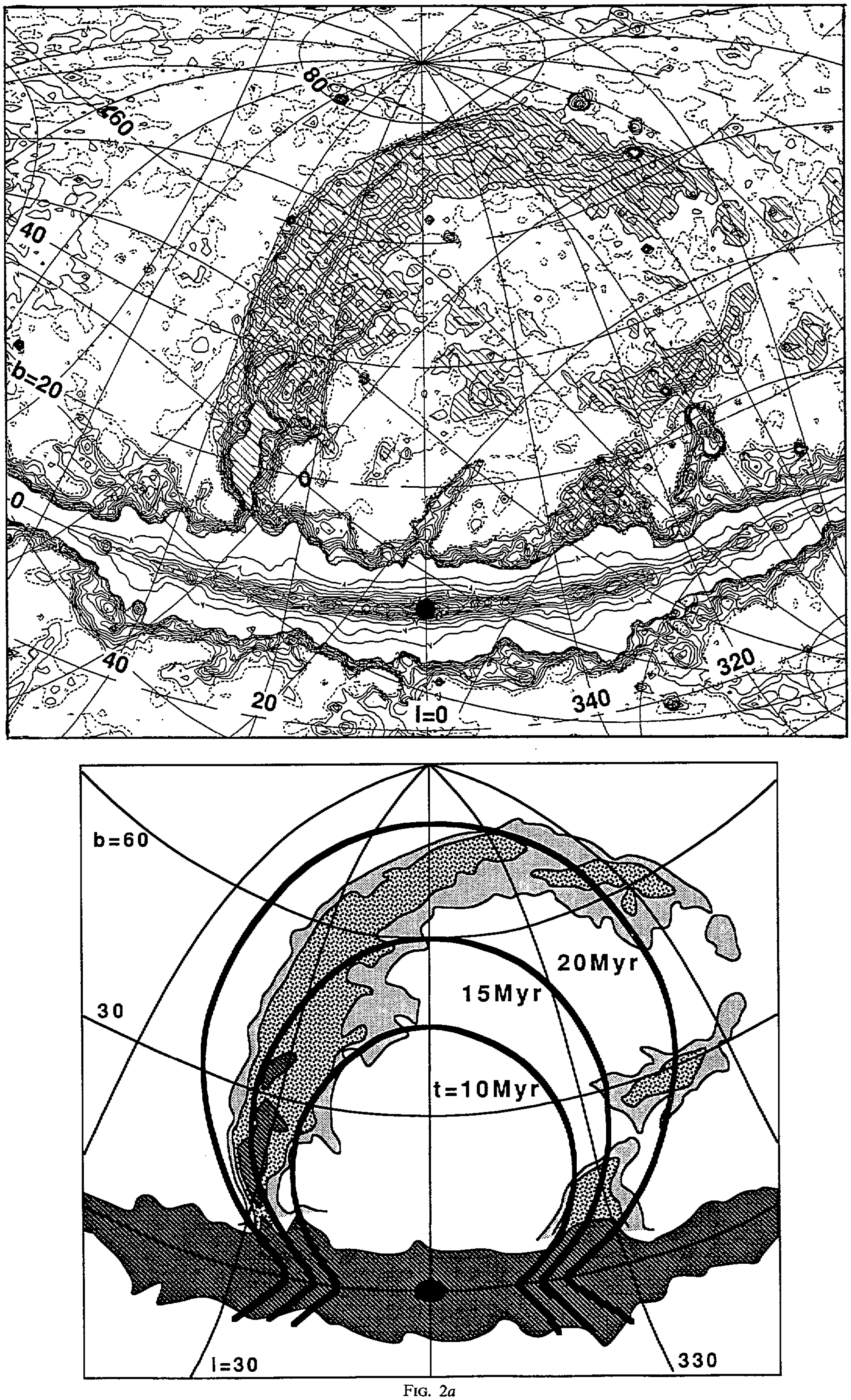

FIG. 2*a*

FIG. 2.—(*a*) North Polar Spur at 408 MHz, showing a giant Ω over the Galactic center, 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 (R.A., Decl.). The calculated shock front is superposed on the sketch of the NPS (*bottom*). (*b*) Same as Fig. 2*a* but in a gray-scale representation.

SOFUE (see 431, L91)

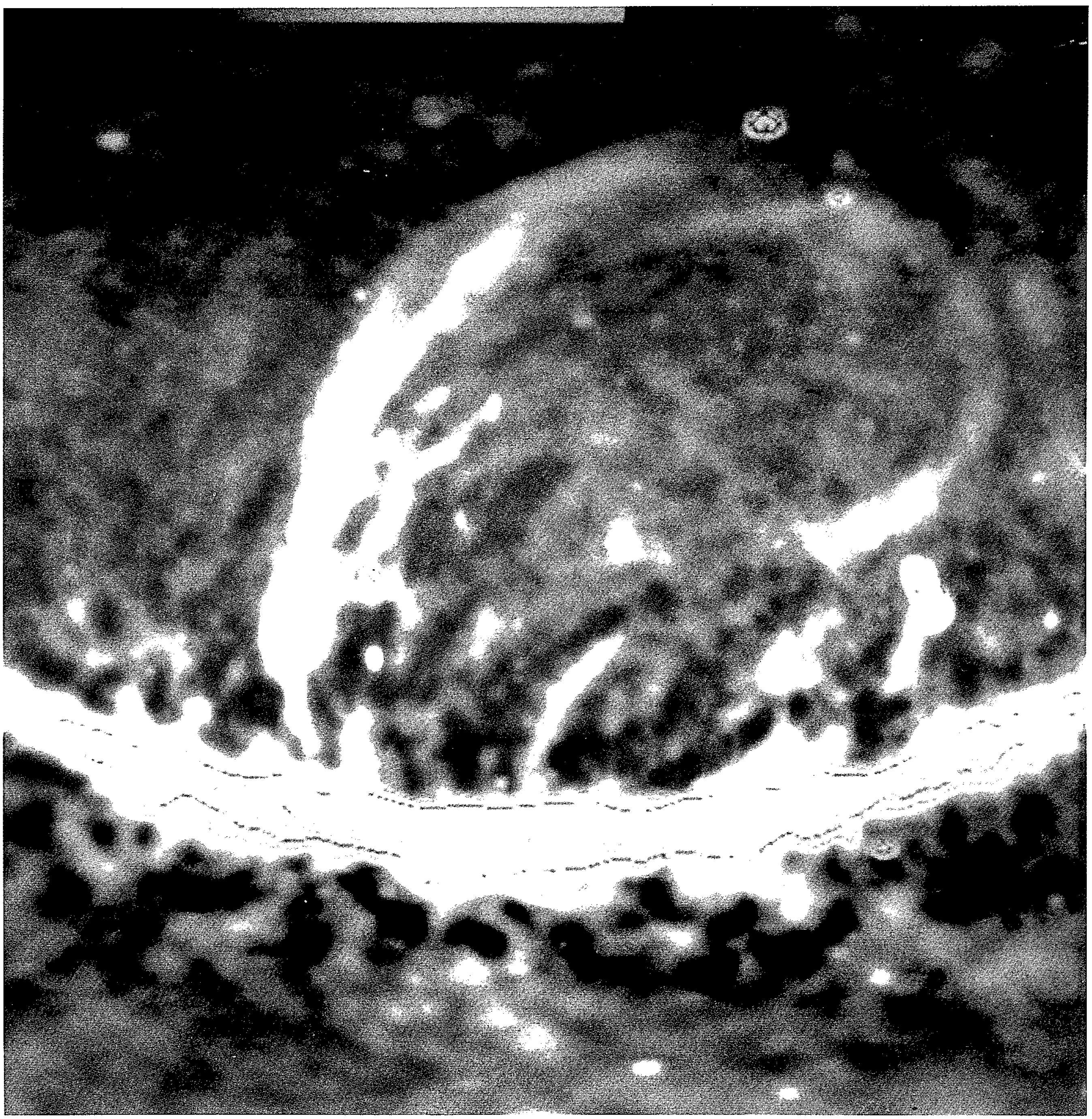

FIG. 2b

SOFUE (see 431, L91)