DARK FILAMENTS IN THE GALAXY NGC 253: A BOILING GALACTIC DISK

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ABSTRACT

We study the morphology of dark lanes and filaments in the dust-rich galaxy NGC 253 using an unsharp-masked B-band optical photograph. Dust features are classified as "arcs," which have heights and scale radius of about 100 to 300 pc, connecting two or more dark clouds, and "loops" and "bubbles," which are developed forms of arcs, expanding into the disk-halo interface. These have diameters of a few hundred pc to ~1 kpc. Among the bubbles, we notice a peculiar round-shaped bubble above the nucleus, which could be a large-diameter (~300 pc) supernova remnant exploded in the halo over the nucleus. We also find "vertical dust streamers," which comprise bunches of narrow filaments with a thickness of a few tens of pc and are almost perpendicular to the galactic plane, extending coherently for 1 to 2 kpc toward the halo. Finally, we note "short vertical dust filaments" (or spicules) are found in the central region. We interpret these features as due to three-dimensional structures of gas extending from the disk into the halo. We propose a "boiling disk" model where the filamentary features are produced by star-forming activity in the disk as well as the influence of magnetic fluxes. We discuss the implication of the model for the chemical evolution of the ISM in a galaxy disk.

1. INTRODUCTION

Vertical dark lanes emerging from galactic disks are often recognized in optical photographs of tilted spiral galaxies, and provide information about the disk-halo interface and the magnetism (Sofue 1987; Sawa & Fujimoto 1987). In addition to vertical lanes, numerous filaments are found in the forms of loops (or bubbles) and arcs, which suggests that the galactic disk is "boiling and steaming" (Sofue *et al.* 1991). These features, particularly coherent bunches of straight vertical filaments, are considered to be deeply coupled with the magneto-hydrodynamical (MHD) activity in galactic disks and halos (Sofue & Fujimoto 1987; Sofue 1991).

In order to investigate such activity, we have undertaken a systematic survey of dark filaments in the nearby Sculptor group galaxy NGC 253. In addition to its proximity [2.5 Mpc (Pence 1980)] this galaxy is inclined at about 78 degrees to the line of sight and so is ideally oriented for this kind of study. (Parameters for NGC 253 are listed in Table 1.) In addition, it is unusually dusty and the dust can be seen in silhouette over most of the inclined disk. Here, we present the result of the survey and describe a morphological classification of the identified features. We further discuss implications for the MHD activity of the various filamentary phe-nomena seen in the disk-halo interface, and propose a "boiling-disk" model.

2. DARK FILAMENTS IN NGC 253

The optical photograph was taken at the $f/3.3$ prime focus of the Anglo-Australian 3.9 m telescope using the triplet cor-rector on a IIIa-J plate combined with a GG385 filter. The plate had been hypersensitized in nitrogen and hydrogen be-fore exposure, which was 80 min long and made (in a nitro-gen atmosphere) on 1979 October 20–21 under excellent seeing conditions. In order to enhance the small scale struc-tures such as filaments, the plate had been copied with the aid of an unsharp mask, which emphasizes the fine detail we are interested in. Figures 1(a)–1(c) show the photographs

TABLE 1. Parameters for NGC 253.

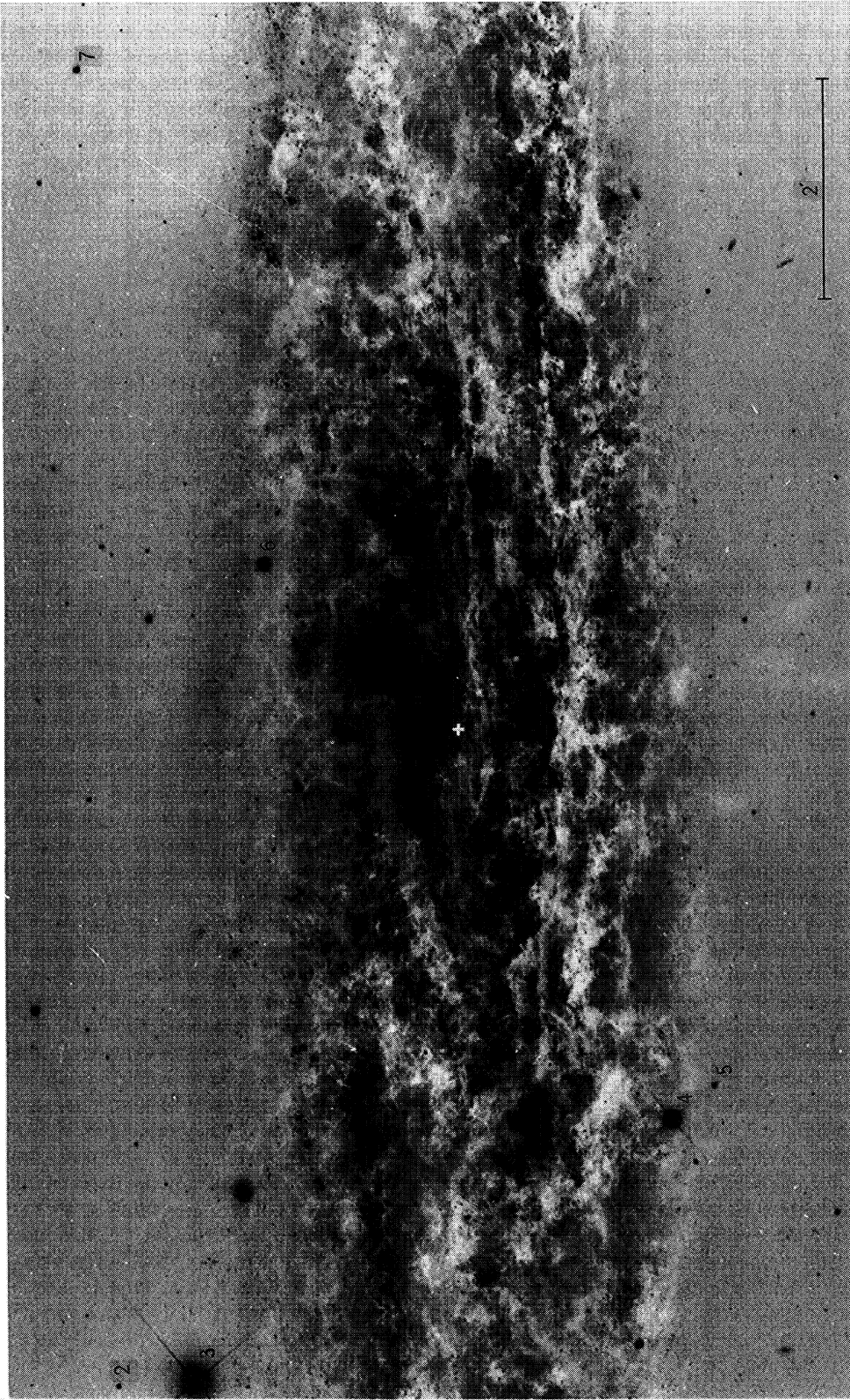| Position of the nucleus[†]	RA=0^h 45^m 05.9^s
	Dec=−25°33′40″.1
Distance	2.5 Mpc (Pence 1980)
Node P.A.	47°
Inclination	78°

[†]NED (NASA Extragalactic Database, IPAC) 1994.

FIG. 1. Unsharp-masked photograph of the galaxy NGC 253. The photograph was taken at the f/3.3 prime focus of the 3.9 m Anglo-Australian Telescope using the triplet corrector on a IIIa-J plate combined with a GG385 filter. (a) The central region of the galaxy; (b) the SW half, and (c) the NE half. Positions of stars 1 to 10 referred to the SAO star (star 3) are given in Table 2. The cross in (a) marks the position of the nucleus.
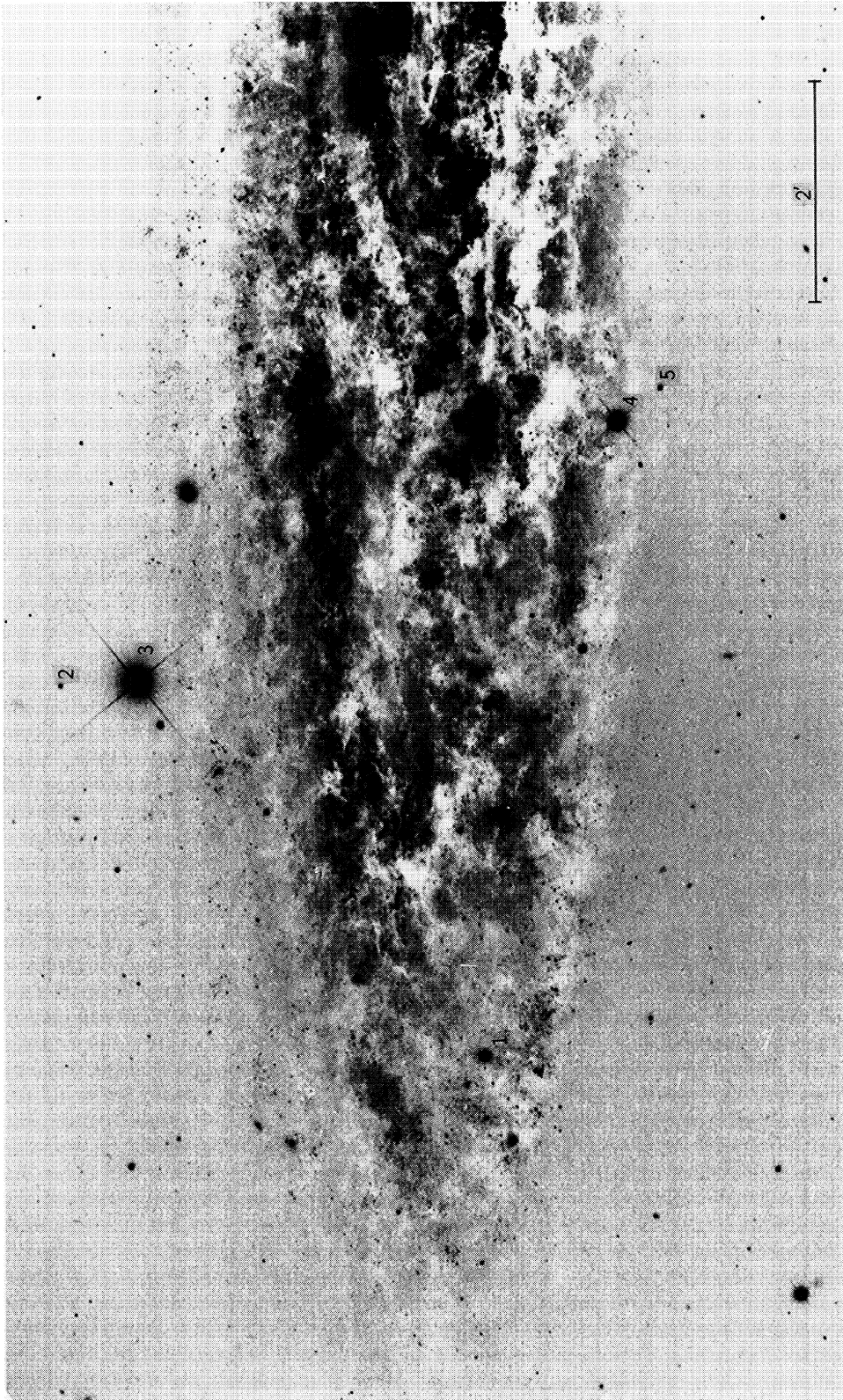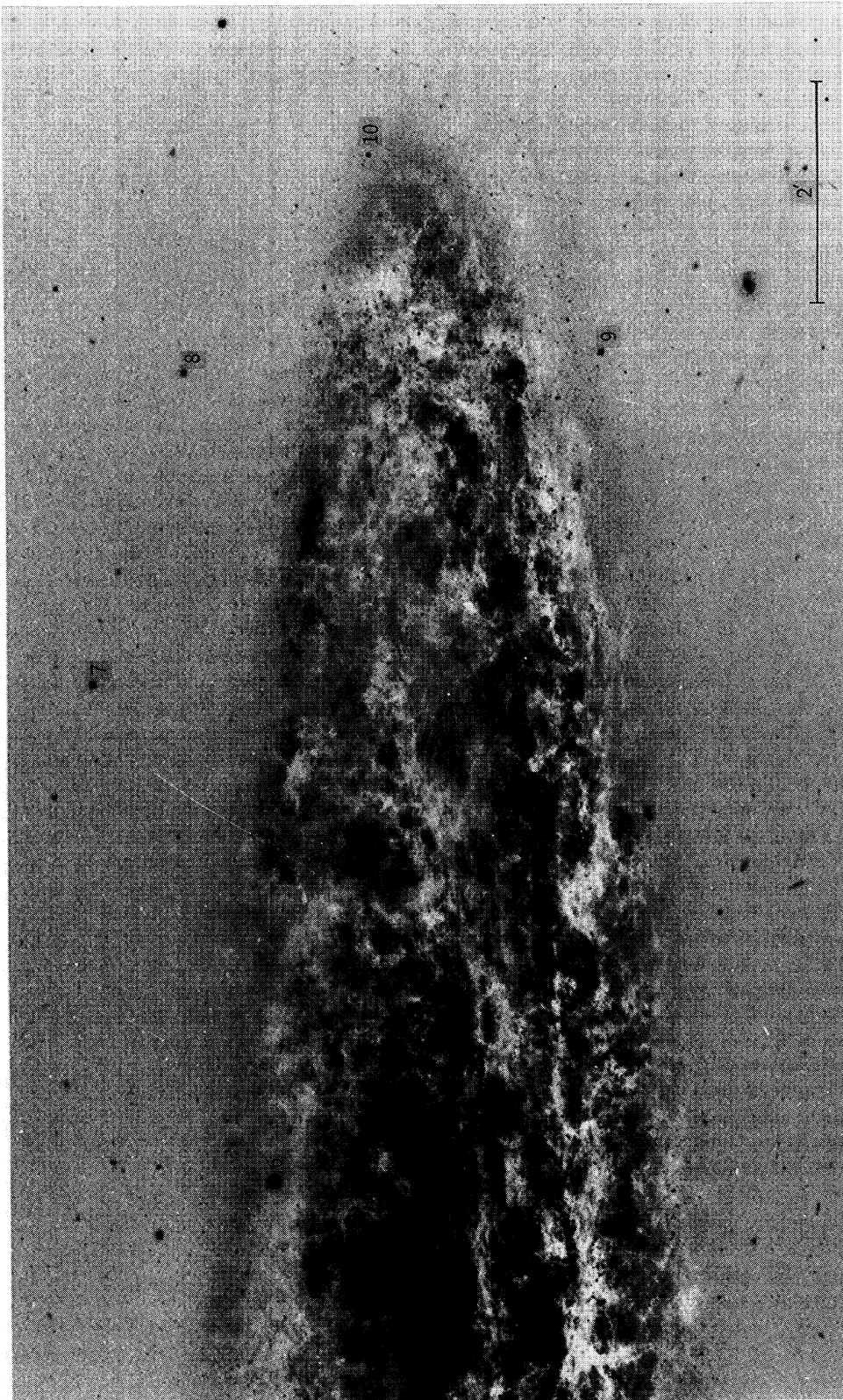
Fig. 1. (continued)

FIG. 1. (continued)

TABLE 2. Equatorial coordinates (1950.0) of the reference stars around NGC 253.

Star	RA (h m s)	Dec(° ′ ″)	$l(°)$	$b(°)$
1	00 44 28.7	−25 39 10	92.69	−87.98
2	00 44 54.5	−25 39 45	95.00	−88.04
3 SAO 166575	00 44 52.8	−25 39 13		
4	00 44 48.4	−25 34 21	95.58	−87.95
5	00 44 48.3	−25 33 52	95.68	−87.94
6	00 45 16.1	−25 33 59	98.30	−87.99
7	00 45 36.1	−25 32 25	100.58	−87.99
8	00 45 43.4	−25 29 58	101.72	−87.96
9	00 45 33.2	−25 26 56	101.23	−87.90
10	00 45 45.3	−25 27 27	102.32	−87.93
Central Bubble	00 45 07.0	−25 33 52	97.45	−87.97

Star 3 was used for the reference of the positions. The distance between stars 3 and 6 is 7.′400=5.38 kpc for a distance of 2.5 MPc of the galaxy; the distance between stars 2 and 5 is 6.′05=4.40 kpc. The error is ±1″.

that resulted for the central region, SW half and NE half of the galaxy. The center of the galaxy (nucleus position) is marked by the cross in Fig. 1(a). On this photograph we notice numerous chaotic features both in emission and the dust lane absorptions in silhouette. We also present a composite color photograph of NGC 253 in Fig. 2 (Plate 79) which has been obtained from three different black and white photographs made in the *B*, *V*, and *R* bands using the same telescope. The scales and positions can be identified by using stars 1 to 10, whose positions are given in Table 2.

2.1 Spiral Arms in Emission and Absorption

Emission regions trace the bright spiral arms, which comprise H II regions and OB associations, seen as red and blue knots (or clumps), respectively, in Fig. 2. Using the unsharp-masked IIIa-J plate copy as well as by referring to the color copy (Fig. 2), we made a sketch of extended emission regions and H II regions. Figure 3 shows the sketch we obtained in this way.

In the same manner, we prepared a sketch of dark lanes, which we show in Fig. 4. Dark lanes are associated with the emission features, tracing the inner edges of the bright arms. The dark lanes are best seen on the unsharp masked derivative of the IIIa-J plate, with the emission features clearly tracing the inner edges of the bright arms. Although these features trace the grand-designed spirals on a galactic scale, they are generally clumpy and bumpy, or flocculent, and consist of numerous clouds of various sizes.

2.2 Dark Filaments

Numerous dust features are found emerging from the dark clouds, apparently "above" the dark lanes and clouds along the spiral arms; Fig. 5 shows a sketch of dark filaments which can be identified on the photograph. Their appearance strongly suggests that the dusty filaments are structures that are vertical with respect to the galactic plane, emerging towards the disk-halo interface and halo. From their morphology, we have classified the dusty filaments into "arcs," "loops" (or bubbles), vertical "streamers," and "short vertical filaments" (or spicules). These classifications are illustrated in Fig. 6.

2.2.1 Arcs

Arcs are filaments with an arch-like structure, bridging two or more dark clouds in the disk. They extend between 100 pc to 1 kpc in length, and about 100 to 300 pc in height. Typical arcs are sketched in Fig. 7. They are usually dome-like, but sometimes show a helmet-like shape, which is suggestive of a relation to magneto-hydro-dynamical phenomenon such as the Parker-type magnetic inflation. The arcs are more often observed in the region of dense spiral arms at galactocentric distances of 2–5 kpc.

2.2.2 Loops and bubbles

Loops are more developed forms of arcs, and their radii are 200 pc to 1 kpc. Some loops appear to be due to projected spherical bubbles, although their three-dimensional structures are not definite from the photograph. Figure 8 reproduces a typical large-scale loop (bubble) found in the north-eastern region, which appears to be expanding into the halo with a diameter of about 0.7 kpc. Besides the dust bubbles and loops, we have noticed an almost spherical hole of dust in the central region, which we describe in detail in Sec. *2.3*.

2.2.3 Vertical dust streamer (VDS)

These are open dust filaments running almost perpendicularly to the galactic plane. They are as thin as a few tens of pc or less (sometimes not resolved with the present 1 arcsec resolution), and lengths of 200 pc to 1 kpc. Numerous vertical dust streamers are found in the central region. The largest VDS are often observed to extend 1 to 2 kpc from the disk, and the largest streamers are found outside the nuclear region, especially in the north-eastern region. We show the largest streamers in Fig. 9, which is located 6.′4 (4.6 kpc) toward the NE from the nucleus. The coherent alignment of these vertical streamers suggests that the filaments are somehow related to vertical magnetic tubes, along which the low-temperature dust is accelerated without being dissociated.

2.2.4 Short vertical filaments

There exist numerous vertical filaments with smaller scales something similar to a brush, very reminiscent of solar spicules. Their shapes are similar to vertical streamers, but scales are much smaller. They are as thin as ten pc or less, not resolved by the present observations. Figure 10 shows the central region where short vertical filaments and numerous long vertical streamers are observed.

2.3 The Spherical Bubble above the Nucleus

In the central region, about 20″ "above" the nucleus, we found an almost perfect spherical structure, which appears as a void (hole) of dusty filaments. Figure 11 shows this "central bubble," and its center position is given in Table 1. The round edge of the hole is outlined by some enhanced dusty filaments. Despite of its huge size (diameter of ~300 pc), it
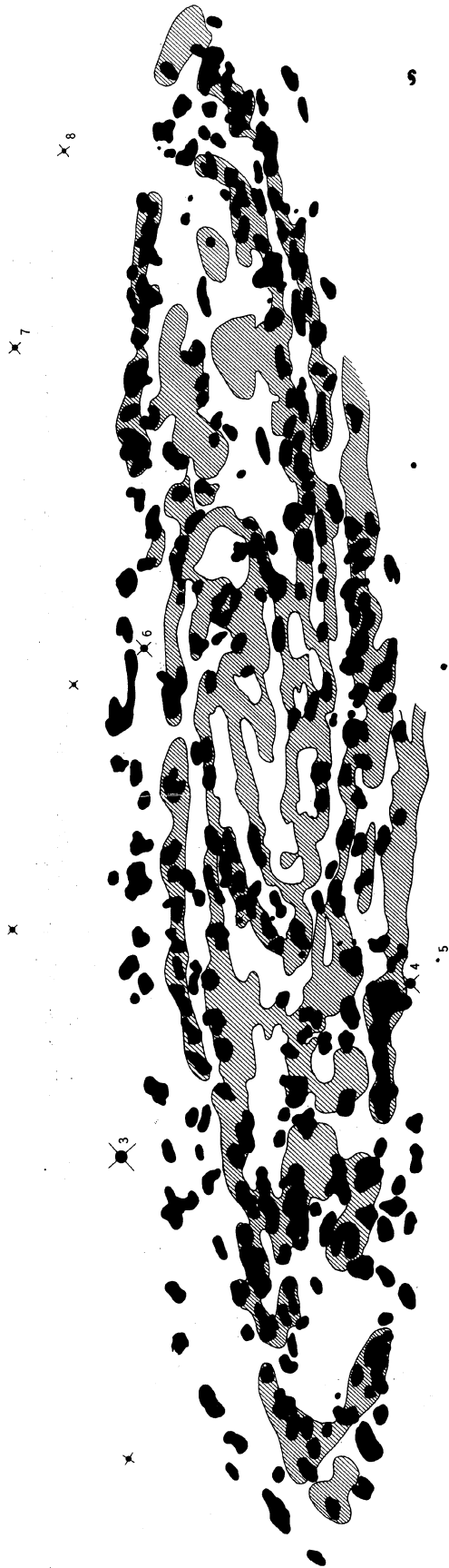
FIG. 3. A sketch of emission regions made from Fig. 1. The emission regions trace spiral structures.

FIG. 4. A sketch of dark lanes, which align predominantly along the spiral arms.

shows no deformation. A bright spiral arm can be traced across the bubble without any interaction, which indicates that the arm is behind this bubble. The velocity field as observed in the CO molecular line shows no particular distortion and hence no interaction with the bubble (Scoville *et al.* 1985). These facts suggest that the bubble is not in touch with the galactic disk, but is located in the halo.

Although the true position of this bubble along the line of sight is ambiguous, the apparent proximity to the nucleus and its location on the minor axis suggest that the bubble is just over the nucleus. If this is the case, the height from the disk is estimated to be about 200 pc. No counterpart to this object is found in the Hα image (Waller *et al.* 1988). No radio map with a sufficient resolution and coverage has been published, so that we cannot investigate its radio properties. An x-ray image at 0.2–4 keV observed with the *Einstein Observatory* shows a feature extending toward the SE along the minor axis in a good positional coincidence with the bubble (Fabbiano & Trinchieri 1984). This bubble object may be a huge spherical ejection from the nucleus. In this context, we mention that the nucleus of NGC 253 is associated with a "superwind" (Heckman *et al.* 1991). It seems likely that the bubble is connected with such a high-velocity outflow, although the spherical shape appears difficult to be explained. Alternatively, from its round and undisturbed appearance, it could be a supernova remnant which has exploded in the halo. However, there still remains a question why the round shape can be retained in spite of the interaction with the superwind.

3. DISCUSSION

3.1 "Boiling-and-Steaming" Disk

The chaotic dusty features as illustrated in Fig. 3 lead us to propose that the gaseous disk of NGC 253 is "boiling," and a part of the gas is "steaming" into the halo. Indeed, streaming motion has been observed along dusty jets in the galaxy NGC 1808 (Phillips 1993). However, understanding the formation mechanism of the out-of-plane dusty filaments observed in NGC 253 remains a challenging problem. The energy source of such turbulence may be the injection of kinetic and thermal energies from supernova explosions as well as by stellar winds. However, acceleration of dust grains up to the heights of a few kpc, while their coherence is preserved, appears difficult to be explained by a direct supply of energy from explosive events without magnetic fields. On the other hand, the morphology of the loops and arcs strongly suggests that they are somehow related to magneto-hydro-dynamical phenomenon such as the expansion of magnetic fluxes. The highly aligned, coherent morphology of the vertical dust streamers also suggests the presence of magnetic lines of force running perpendicularly to the galactic plane. In the following, we suggest possible mechanisms which might produce such coherent bunches of dusty filaments, and discuss the energetics.

3.2 Energetics

The average strength of magnetic fields in the disk of NGC 253 has been estimated to be 13±4 µG (e.g., Sofue

FIG. 5. A sketch of dark filaments, which comprises dark arcs, loops and/or bubbles, vertical streamers, and short dust filaments.

et al. 1986). The field strength in the halo will be weaker, and we may suppose that the field strength in the halo-disk interface at height 100 to 1000 pc would be of the order of one to a few μG. The magnetic energy involved in a typical arc-shaped magnetic flux of strength 1 μG with a radius 300 pc and width 100 pc is, therefore, estimated to be $\sim 10^{50}$ erg, and $\sim 10^{51}$ erg for a field of 3 μG. The gravitational energy required to lift a gaseous mass of the same volume with a density of 10^{-2} H cm^{-3} to a height of $h_z \sim 300$ pc is estimated to be $E_{\mathrm{grav}} \sim m_{\mathrm{gas}} k_z h_z^2 \sim 10^{50}$ erg, about the same as the magnetic energy, where k_z is a constant related to the gravitational acceleration $g_z(z)$ in the z direction as $g_z(z) \simeq k_z z$, and h_z is the scale thickness of the stellar disk. These amounts of energy are comparable to kinetic energy supplied by a single supernova and/or by a stellar wind from a cluster of OB stars. Hence, it will be energetically possible to produce the chaotic three-dimensional dust features in NGC 253 by successive explosions of SN in the disk as well as from stellar winds from massive stars.

3.3 Magnetic Flux Inflation

It is possible that dust grains coexist with partially ionized gas which is entrained in a magnetic field. If the magnetic inflation occurs in a time scale (t_m) short enough compared to the infall time of the gas from the halo (t_g), dust grains can be carried to the height by the inflating magnetic fluxes. The time scales are given by

$$t_m \sim z/V_A \sim \sqrt{4\pi\rho}\, z/B$$

$$\sim 10^7 \frac{z}{300 \text{ pc}} \left(\frac{\rho}{0.01 m_H \text{ cm}^{-3}} \right)^{1/2}$$

$$\times \left(\frac{B}{10^{-6} \text{ G}} \right)^{-1} \text{ yr}, \qquad (1)$$

where V_A is the Alfven velocity, z is the height from the galactic plane, ρ is the density of gas in the magnetic tube, and B is the field strength. If we take $\rho \sim 10^{-2} m_H$ cm^{-3} and $B \sim 10^{-6}$ G, we have $t_m \sim 10^7$ yr for $z \sim 300$ pc.

The gas infall time is given by

$$t_g \sim 1/\sqrt{k_z} \sim h_z/v_z \sim 10^7 \frac{h_z}{300 \text{ pc}} \left(\frac{v_z}{30 \text{ km s}^{-1}} \right)^{-1} \text{ yr}, \qquad (2)$$

where v_z is the velocity dispersion of disk stars in the z direction. For a normal galactic disk we may take $h_z \sim 300$ pc and $v_z \sim 30$ km s^{-1}, then we have $t_g \sim 10^7$ yr. Hence, if the magnetic strength is greater than 1 μG and/or the gas density within magnetic tubes is less than some $\sim 0.01 m_H$ cm^{-3}, raising the dust grains to the observed height is possible.

3.4 Acceleration by Radiation-Pressure along Magnetic Tubes

The radiation pressure due to starlight from the disk and bulge, particularly from starburst regions, would act to drive (accelerate) dust grains along vertical magnetic tubes, pro-

FIG. 6. Classification of the major filamentary features into arcs, loops and/or bubbles, long vertical streamers, and short vertical filaments.
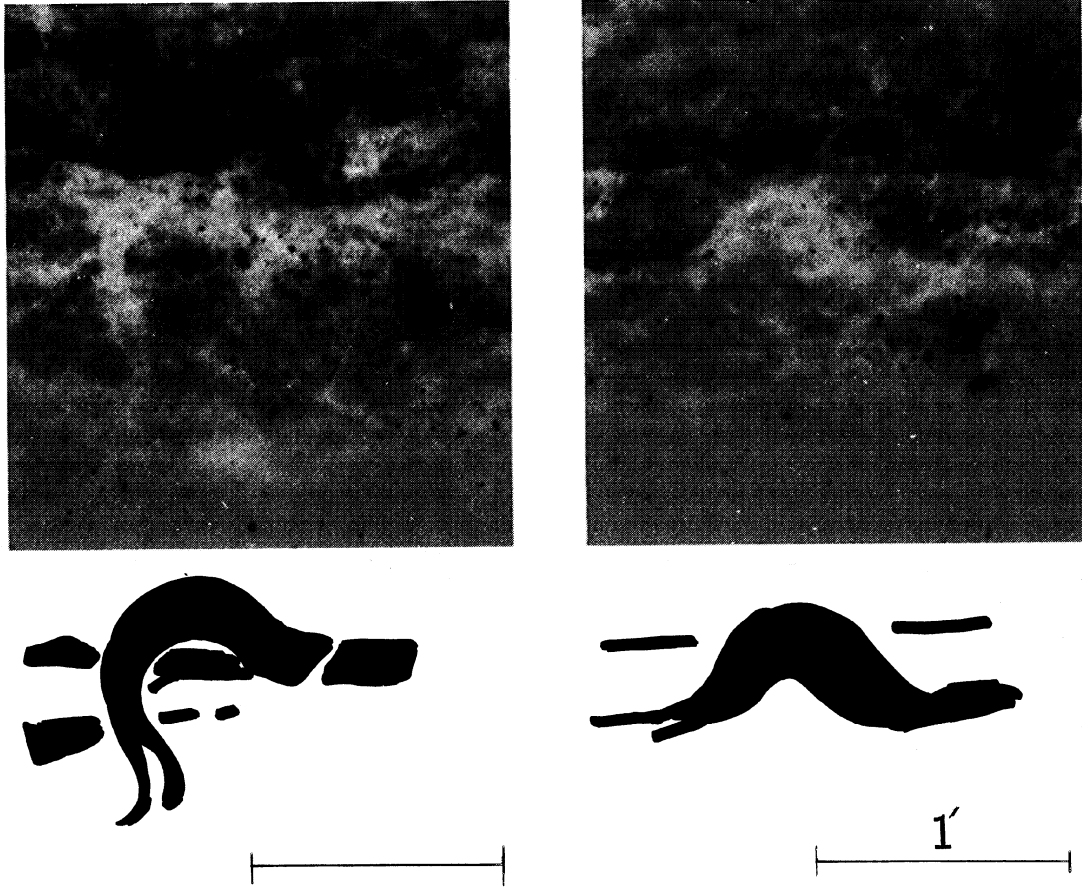
FIG. 7. Arcs.

ducing vertical dusty structures (Franco *et al.* 1991). The time scale of a grain to be accelerated to a height z by the radiation pressure is roughly estimated by

$$t_{rad} \sim \sqrt{a \rho_d z c / I}$$

$$\sim 2 \times 10^7 \left(\frac{a}{1 \ \mu m} \right)^{1/2} \left(\frac{\rho}{1 \ g \ cm^{-3}} \right)^{1/2}$$

$$\times \left(\frac{z}{300 \ pc} \right)^{1/2} \left(\frac{I}{10^{44} \ erg \ s^{-1}/(\pi 10 \ kpc)^2} \right)^{-1/2} \ yr, \tag{3}$$

where a and ρ_d are the size (radius) and density of the grain, respectively, c is the light velocity, and I is the intensity of star light which can be approximated by $I \sim L/(\pi R^2)$ with L and R being the luminosity and effective radius of the galaxy disk, respectively. If we take $a \sim 1 \ \mu m$, $\rho_d \sim 1 \ g \ cm^{-3}$, $z \sim 300$ pc, $L \sim 10^{44}$ erg s^{-1}, and $R \sim 10$ kpc, then we have $t_{rad} \sim 2 \times 10^7$ yr. This is in the same order as the infall time, and, therefore, the acceleration of dust grains is quite possible.

In order for the magnetic lines of force to act as guide lines (or tubes) for dust grains blown by stellar radiation pressure, the strength of the magnetic field must be strong enough, or $t_{mag} \ll t_{rad}$. The radiation pressure as well the magnetic field strength in the central few kpc region of the gal-

axy would be much stronger than the values assumed above, and, therefore, the acceleration due to the radiation pressure would be more effective in the central region than in the outer region. In fact, the vertical streamers and short filaments are more often observed in the central region.

3.5 Implications for the Chemical Evolution of the ISM

We have obtained the morphological classification of dark lanes and filaments in the galaxy NGC 253. The features are naturally understood if they are out-of-plane structures, emerging from the galactic plane toward the halo, and appear to establish a disk-halo interface. We have suggested some possible mechanism for the formation of the vertical structures and given arguments about the energetics involved. However, individual features are too complicated to be explained by such simple mechanisms, and we have to wait for a detailed theoretical modeling, particularly by taking into account MHD activities in the disk-halo interface. It is also necessary to obtain further information about kinematics and quantitative estimates of the masses and magnetic fields involved in the features.

The outflow of gas from the galactic disk has implications for the circulation of interstellar gas. Particularly, such an energetic ejection as the large-scale vertical dust streamers
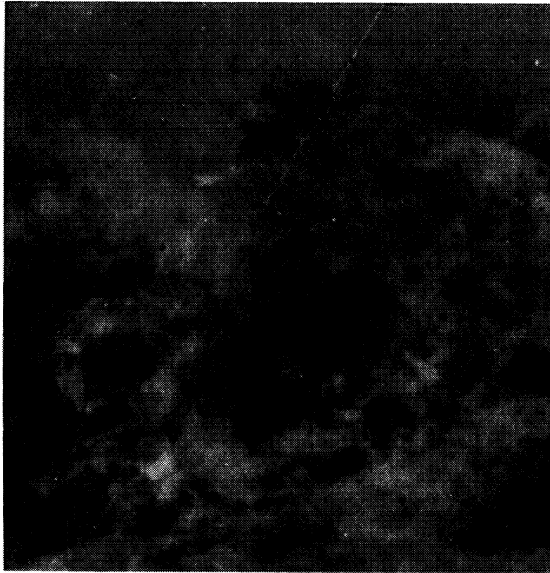
19.6p

FIG. 8. Loops and bubbles.

will play a significant role in lifting the "metal-polluted" (or metal-enriched) interstellar gas into the halo. The gas lifted to the halo will then fall back to the disk at different locations, causing a mixing of the ISM. If the gas is blown off far away from the central region by the radiation pressure due to strong starlight from the nuclear region, it will fall on the outer disk. This would then result in a galactic scale mixing (circulation) of dusty gas from the inner to outer disk. This

will inevitably result in a galactic-scale mixing of heavy elements, and therefore, a smearing out the metallicity gradient with respect to galactocentric distance. The increase in metallicity enhances the formation of dust and molecular clouds, so the large-scale circulation of the metallicity results in the increase of the star-formation rate in the outer disk: The boiling-and-steaming disk phenomenon would, therefore, affect the chemical evolution of a disk galaxy.

FIG. 9. The largest-scale vertical dust streamers in the NE.

Fig. 10. Short vertical filaments (spicules) in the central region. The cross marks the position of the nucleus.
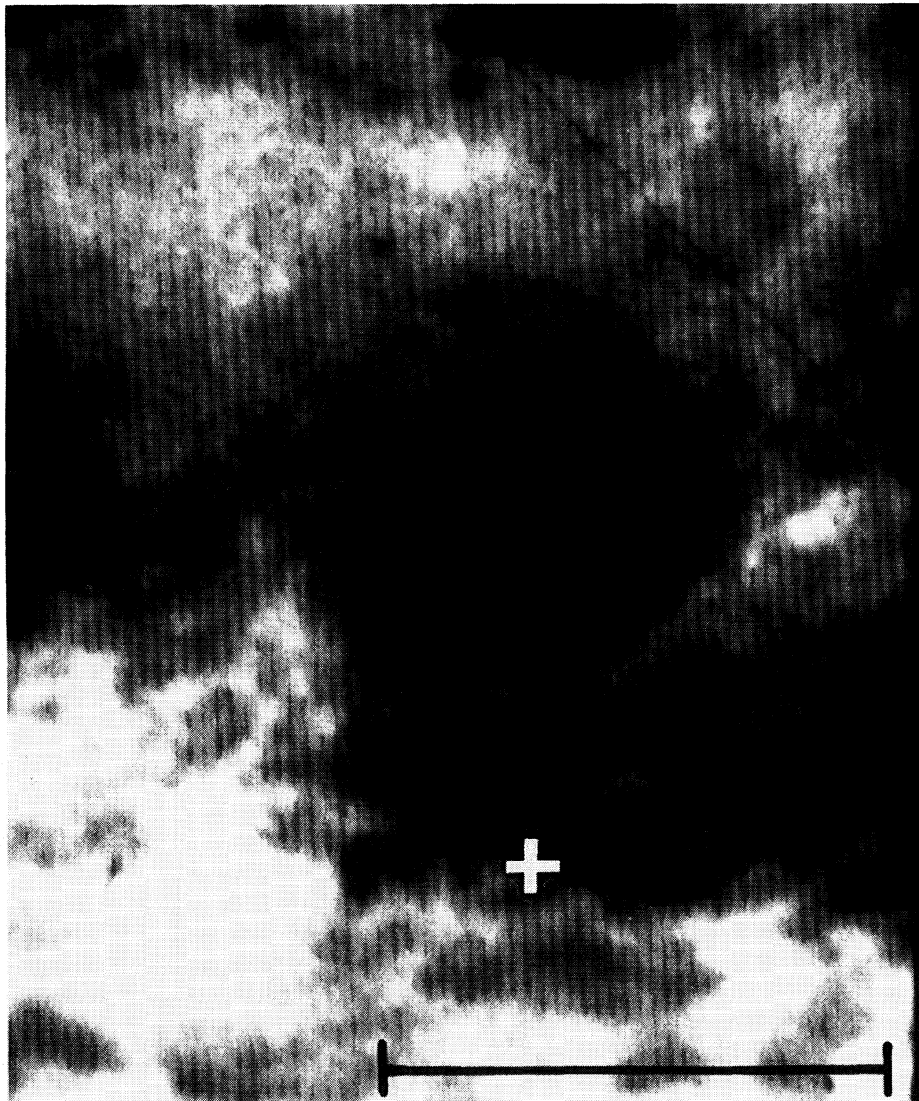
FIG. 11. The spherical bubble (hole) "above" the nucleus (marked by the cross). The diameter of the bubble is approximately 300 pc. The bar indicates 30″=366 pc.

REFERENCES

Fabbiano, G., & Trinchieri, G. 1984, ApJ, 286, 491

Franco, J., Ferrini, F., Ferrara, A., & Barsella, B. 1991, ApJ, 366, 443

Heckman, T. M., Armus, L., & Miley, G. K. 1991, ApJS, 74, 833

Pence, W. D. 1980, ApJ, 239, 54

Philips, A. 1993, AJ, 105, 486

Sawa, T., & Fujimoto, M. 1987, in Magnetic Fields and Extragalactic Objects, edited by E. Asseo and D. Greésillon (Edition de Phys.), pp. 165–169

Scoville, N. Z., Soifer, B. T., Neugebauer, G., Young, J., & Yerka, J. 1985, ApJ, 299, 129

Sofue, Y. 1991, in The Interstellar Disk-Halo Connection in Galaxies, IAU Symposium No. 144, edited by J. B. G. M. Bloemen (Kluwer, Dordrecht), p. 169

Sofue, Y. 1987, PASJ, 39, 547

Sofue, Y., & Fujimoto, M. 1987, PASJ, 39, 843

Sofue, Y., Fujimoto, M., & Wielebinski, R. 1986, ARA&A, 24, 459

Sofue, Y., Y., Wakamatsu, K., & Malin, D. F. 1991, in The Interstellar Disk-Halo Connection in Galaxies, IAU Symposium No. 144, edited by J. B. G. M. Bloemen (Kluwer, Dordrecht), p. 309

Waller, W. H., Kleinmann, S. G., & Ricker, G. R. 1988, ApJ, 95, 1057

PLATE 79

FIG. 2. Natural-color photograph of NGC 253, as obtained from three different color photographs using the same telescope as for Fig. 1.

Sofue *et al.*(see page 2106)

2376