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# Vertical Dust Lanes and Magnetic Field in Spiral Galaxies

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## Abstract

Dark filaments (dust lanes) vertically emerging toward the halo from the 3–4-kpc molecular ring in the disk plane are found in the spiral galaxies NGC 253 and NGC 7331. The filamentary structure of dust is interpreted as a trace of a vertical magnetic field penetrating the galaxy disk. The vertical field, being twisted by galactic rotation, is suggested to yield an outflow of disk matter into the halo, which we call a "magnetic fountain" of galaxy scale. The magnetic fountain is suggested to be a possible formation mechanism of radio halos in these galaxies. A more condensed vertical field in the central region may be related to a mass ejection from the nucleus of NGC 253.

Key words: Active galactic nuclei; Dust lanes; Galaxies; Magnetic fields.

## 1. Introduction

The large-scale magnetic field in spiral galaxies has been extensively studied through radio and optical polarization observations [Sofue et al. (1986), and the literature cited therein]. In these studies the authors have always been concerned with magnetic field confined in the disk of a galaxy, whereas very little attention has been paid to a large-scale vertical component of magnetic field. Such a vertical component must inevitably exist, if we adopt the primordial origin hypothesis of the galactic magnetic field. In fact the majority of spiral galaxies possess a predominant bisymmetric spiral (BSS) configuration of magnetic field, and the configuration is better understood by the primordial origin hypothesis (Sofue et al. 1986) than by the dynamo-generation mechanism (Paker 1971). In this hypothesis the intergalactic magnetic field was trapped in a protogalaxy and wound up by the differential rotation of the disk gas. The disk component is then maintained in a steady-state BSS configuration through the cyclonic dynamo process (Sawa and Fujimoto 1986), while

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the vertical component remains obeying the flux conservation and is conveyed to the central region.

The first attempt to discuss the vertical (poloidal) component of a large-scale magnetic field in a spiral galaxy was made by Sofue and Fujimoto (1987). It was shown that a large-scale vertical field trapped in a protogalaxy is effectively conveyed to the central region, where the field is tightly accumulated to compose a vertical structure fixed to the gas disk. The importance of a vertical field in the central region has been stressed in relation to the activity of cosmic jet formation (Uchida and Shibata 1986).

Observationally a vertical field has been found in the central ~100 pc of our Galaxy through radio polarization observations (Yusef-Zadeh et al. 1984; Tsuboi et al. 1986; Sofue et al. 1987). In external galaxies, however, no clear evidence for a vertical magnetic field has been obtained yet. Current observations have provided data only useful for discussing the disk component, or at least the data have been interpreted in terms of the disk field. Neither radio nor optical polarization data are available for the halo emission to derive the vertical field.

In this paper we present the result of an attempt to find an indication of a vertical structure in spiral galaxies. We try to search for dust lanes, or dark filaments, that emerge from the galactic plane of nearby galaxies using the photographs in the *Hubble Atlas of Galaxies* (Sandage 1961). We discuss the structures with particular regard to the vertical magnetic field structure and a jet formation activity in the central regions.

## 2. Vertical Dust Lanes

In order to trace vertical structures seen as dark filaments emerging from the disk plane, we need to properly select spiral galaxies so that they satisfy the following criteria:

(a) Rich in interstellar dust grains;

(b) Bulge emission is not dominant so that inner dust lanes can be seen. Sb and Sc galaxies are more appropriate than Sa;

(c) Inclination is appropriate so that the veritcal dust lanes are seen clearly with the background of central bulge emission or the inclination angle lying between $i\sim 60°$ and $80°$ ($i=90°$ for edge-on);

(d) Nearby enough to us so that the dust filaments can be resolved using the existing imaging techniques;

(e) The disk structure is not strongly disturbed; namely, irregular and peculiar galaxies may be excluded.

Considering these criteria, we selected spiral galaxies using the *Palomar Sky Survey* prints, the *Second Reference Catalogue of Galaxies* (de Vaucouleurs et al. 1976), the *Revised Shapley–Ames Catalog of Bright Galaxies* (Sandage and Tammann 1981), and the *Hubble Atlas* of *Galaxies* (Sandage 1961). Table 1 lists the galaxies thus selected with the major diameters greater than ~1′. The majority of the galaxies cannot be studied here, because no good-quality photographs are available from the literature. Only for four galaxies, M31, M81, NGC 253 and NGC 7331, high-quality

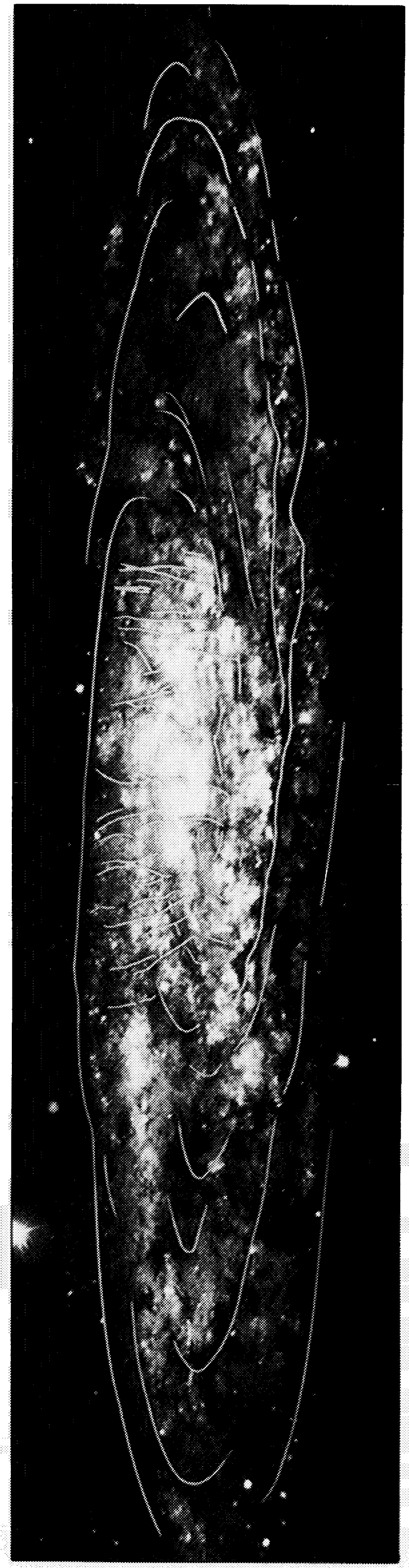
Table 1. Tilted, nearby Sb and Sc galaxies for a study of vertical dust lanes.

| Galaxy | Type | $D$ (arcsec) | $R$ | $i$ (degree) | $v$ (km $s^{-1}$) | Remarks |
|---|---|---|---|---|---|---|
| NGC 224, M31 | Sb | 1780 | 2.82 | 74 | −297 | H18 |
| NGC 247 | Sc | 200 | 2.69 | 68 | 156 | |
| NGC 253 | Sc | 257 | 3.39 | 78 | 245 | H34, VDL, see text |
| NGC 891 | Sb | 153 | 4.79 | Edge-on | 530 | H25, many VDL |
| NGC 1055 | Sbc, pec | 76 | 2.51 | Edge-on | 993 | |
| NGC 1337 | Sc | 67 | 3.31 | 72 | 1237 | |
| NGC 2683 | Sb | 93 | 3.72 | Edge-on | 404 | |
| NGC 2841 | Sb | 81 | 2.14 | 62 | 637 | H14 |
| NGC 2903 | Sc | 126 | 1.91 | 58 | 550 | H35 |
| NGC 3003 | Sc | 59 | 3.39 | Edge-on | 1481 | |
| NGC 3031, M81 | Sb | 240 | 1.82 | 57 | −36 | H19, see text |
| NGC 3034, M82 | pec | 112 | 2.45 | Edge-on | 247 | H41, amorphous long VDL |
| NGC 3079 | Sc | 76 | 4.47 | Edge-on | 1130 | |
| NGC 3198 | Sc | 83 | 2.24 | 64 | 130 | |
| NGC 3432 | Sc | 62 | 3.98 | Edge-on | 616 | |
| NGC 3521 | Sb | 95 | 1.91 | 58 | 818 | H15 |
| NGC 3556 | Sc | 83 | 3.89 | Edge-on | 698 | H35, VDL? |
| NGC 3623 | Sa | 100 | 3.02 | 71 | 805 | H11 |
| NGC 3627 | Sb | 87 | 2.00 | 60 | 723 | |
| NGC 3628 | Sbc, pec | 148 | 4.07 | Edge-on | 847 | |
| NGC 4096 | Sc | 65 | 3.63 | 72 | 560 | |
| NGC 4157 | Sbc | 69 | 4.17 | Edge-on | 780 | |
| NGC 4192 | Sb | 86 | 3.02 | 71 | −140 | |
| NGC 4216 | Sb | 82 | 3.80 | Edge-on | 111 | H25, VDL similar to NGC 7331 |
| NGC 4244 | Scd | 162 | 6.46 | Edge-on | 242 | H25 |
| NGC 4258, M106 | Sb | 182 | 2.29 | 64 | 463 | H33 |
| NGC 4501 | Sbc | 69 | 1.78 | 56 | 2269 | |
| NGC 4517 | Sc | 102 | 5.37 | Edge-on | 1129 | |
| NGC 4527 | Sb | 63 | 2.75 | 69 | 1738 | |
| NGC 4536 | Sc | 74 | 2.14 | 62 | 1809 | |
| NGC 4559 | Sc | 105 | 2.14 | 62 | 810 | |
| NGC 4565 | Sb | 162 | 5.89 | Edge-on | 1220 | H25, VDL |
| NGC 4569 | Sab | 95 | 2.04 | 61 | −260 | H13 |
| NGC 4594, M104 | Sab | 89 | 2.19 | 84 | 1089 | H24 |
| NGC 4631 | Sc | 151 | 4.57 | Edge-on | 619 | H25 |
| NGC 4826 | Sb | 93 | 1.74 | 55 | 413 | H13, DL cross bulge |
| NGC 5033 | Sbc | 105 | 1.86 | 58 | 878 | |
| NGC 5746 | Sb | 79 | 4.57 | Edge-on | 1731 | |
| NGC 5907 | Sc | 123 | 6.92 | Edge-on | 621 | H25 |
| NGC 7331 | Sb | 107 | 2.69 | 69 | 820 | H17, VDL, see text |
| NGC 7640 | SBc | 107 | 4.27 | Edge-on | 368 | H49 |

$D$ is the major Holmberg diameter, $R$ the ratio of the major and minor diameters, both taken from the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs et al. 1976). The inclination was calculated from $R$ except for edge-on cases, and galaxies with $i \lesssim 60°$ have been avoided. The type and radial velocity were taken from *A Revised Shapley–Ames Catalog of Bright Galaxies* (Sandage and Tammann 1981). VDL stands for "vertical dark (dust) lanes." H18 etc. denotes page number (p. 18 etc.) in the *Hubble Atlas of Galaxies* (Sandage 1961).

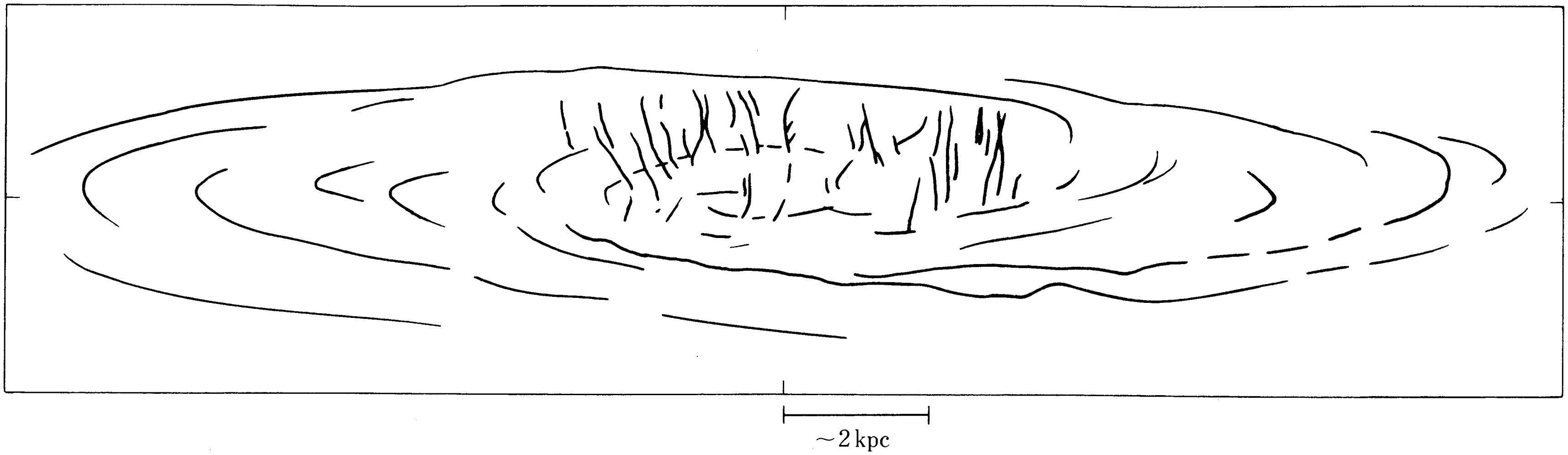
~2 kpc

(a)



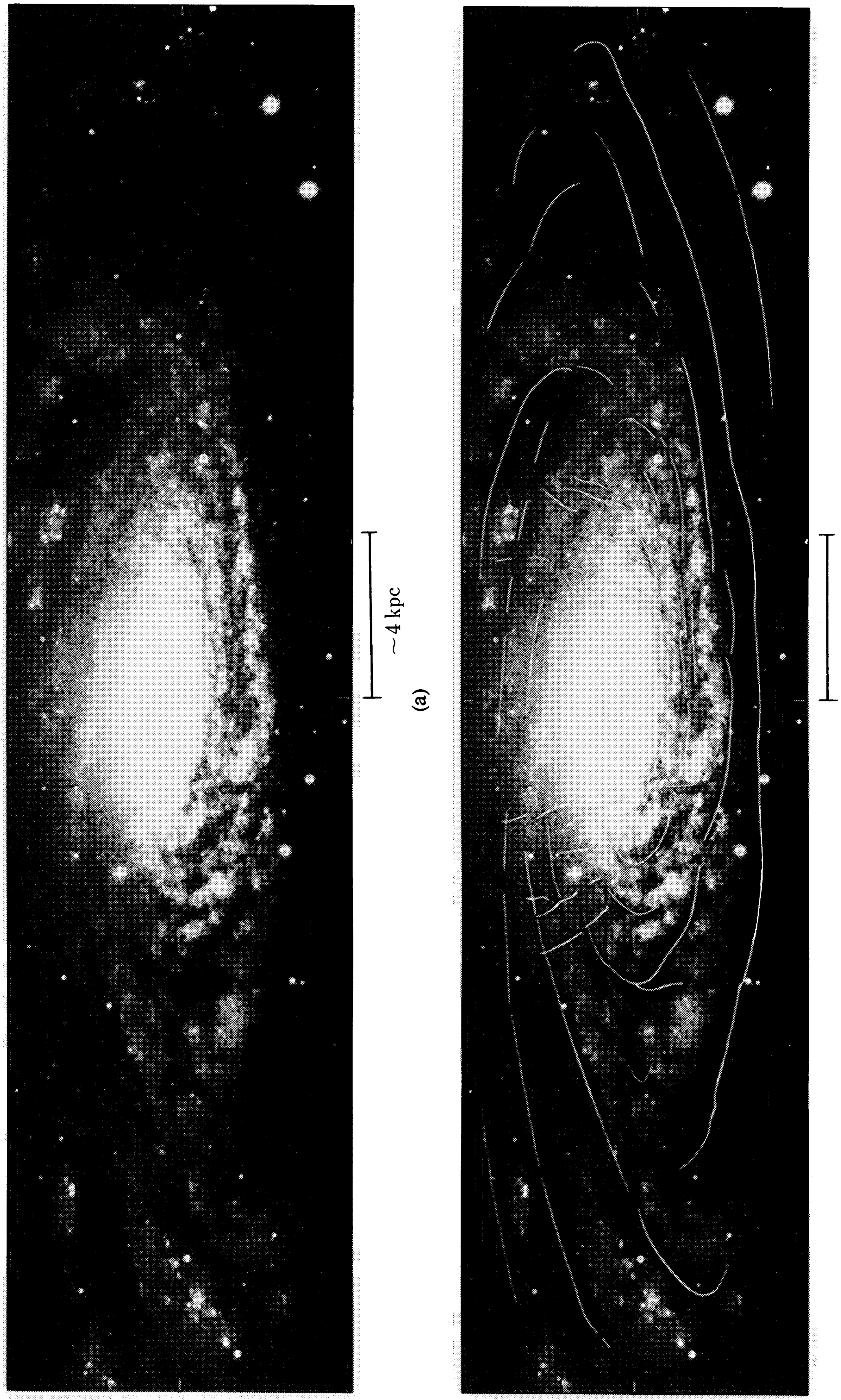
~2 kpc

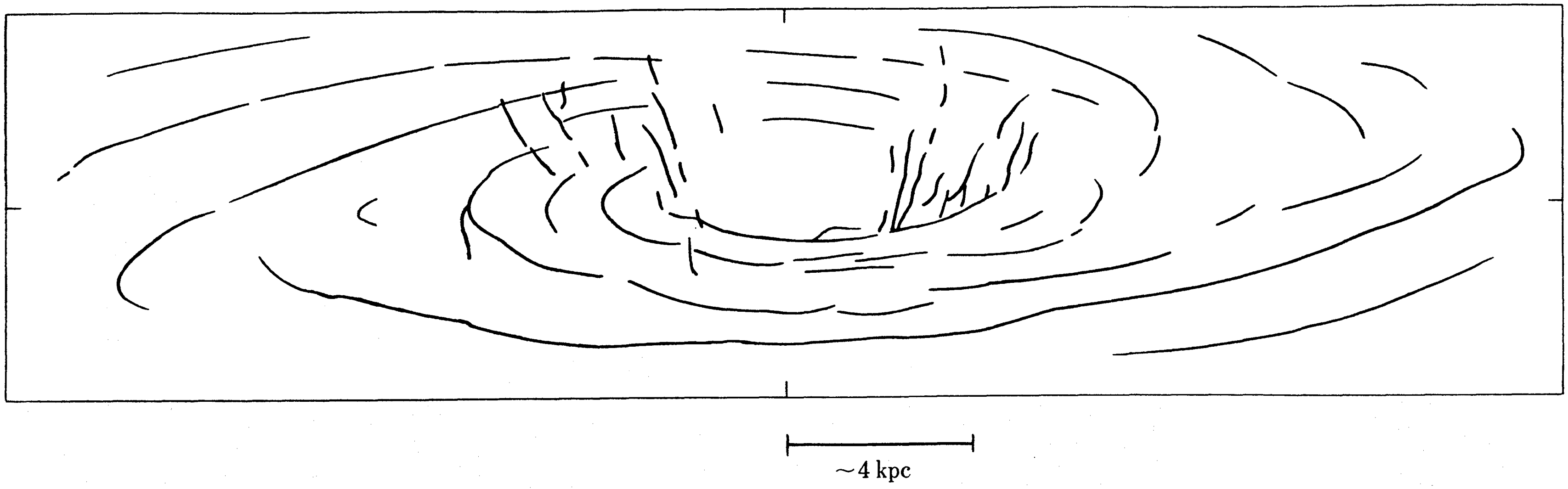
(b)




(c)

Fig. 1. (a) A photograph of NGC 253 reproduced from the *Hubble Atlas of Galaxies* (Sandage 1961; copyright © by Carnegie Institution of Washington). Note the vertical dark filaments running from the disk plane in the central region of $R<2$ kpc, which we interpret as a trace of a vertical magnetic field penetrating the disk plane. (b) Superposition of (a) and (c). (c) A schematic sketch of the vertical dark filaments in NGC 253.


~4 kpc
(a)
~4 kpc
(b)




(c)

Fig. 2. (a) A photograph is reproduction of NGC 7331 from the *Hubble Atlas of Galaxies* (Sandage 1961; copyright © by Carnegie Institution of Washington). Note the dark filaments running perpendicular to the major axis, which we interpret as a trace of a large-scale vertical magnetic field. (b) Superposition of (a) and (c). (c) A schematic sketch of the vertical dark filaments in NGC 7331.

photographs are available in Sandage (1961). Among them, however, M31 is not rich enough in dust grains so that the structures in the central regions are not clealry seen on the photograph as dark filaments. We here discuss in some detail NGC 253, NGC 7331, and M81.

### *2.1. NGC 253*

In figures 1a and b we reproduce a photograph of NGC 253 from the *Hubble Atlas of Galaxies* (Sandage 1961). This is an Sc galaxy rich in clumpy dust lanes. The distance and inclination are 3.4 Mpc (Sandage and Tammann 1975) and $i=78°$ (Sandage 1961). Although the dust clumps in the outer regions seem to spread both in the vertical and horizontal directions, it is not clear if a large-scale vertical structure exists. On the other hand, in the central region at a galactocentric distance $R<200''$ ($\sim$3 kpc), we can recognize a number of dark filaments running almost perpendicular to the major axis crossing the spiral arms.

Figures 1b and c show a sketch of the distribution of the vertical dark filaments. From the fact that they cross more than one arm on the farther side of the disk plane, they are not a structure in the galaxy plane but are located between the farther-side arms and the observer. Moreover, they have their roots in the dusty regions of the nearer-side spiral arms. From these facts, we may conclude that the dark filaments are a vertical structure composed of dust lanes emerging from the disk plane. The length of the filaments is more than $80''$ ($\sim$1.3 kpc), if they are perpendicular to the disk plane. (If the features lie in the disk, their length must be more than 6 kpc crossing the arms and this is very unlikely.) Individual filaments are very thin with a typical width of roughly $\sim$40 pc. The filaments are slightly inclined toward the outer radius, or they appear to have an opening angle of about 20–30° with the minor (rotation) axis.

### *2.2. NGC 7331*

This is a dust-rich, Sb spiral galaxy with an inclination angle $i=69°$ and a distance $D=13$ Mpc (Klein et al. 1984). Figures 2a and b reproduce an optical photograph from the *Hubble Atlas of Galaxies* (Sandage 1961). A careful inspection of the photograph reveals again vertical dark filaments, apparently crossing the spiral arms, in the central region of $R<60''$ ($\sim$3 kpc) and most prominent at $R\sim50''$. They are very similar to those found in NGC 253 but are more clearly seen against the bright central bulge as background. For the same reason as for the case of NGC 253 we may conclude that they are structures perpendicular to the disk plane. The filaments form dark lanes running toward the halo with an opening angle of $\sim$20° with the minor axis. The filaments reach as high as $\sim$2 kpc ($30''$) from the disk plane and are as thin as $\sim$100 pc. They have their roots in dusty regions of the spiral arms. Figures 2b and c show a sketch of the vertical dark filaments.

### *2.3. M81 (NGC 3031)*

Sandage (1961) noticed an intricate dust pattern at the south end of the major axis and an even more intricate pattern of straight dust lanes, which has no connection with the spiral structure, on the north-preceding end of the major axis. He noted that the parallel streaks can be traced across the central lens and across two branches of the brighter spiral arm on the north-preceding side. These streaks may originate either from the dust inside M81 or due to the foreground dust, e.g., dust in our Galaxy. The southern dust lanes are likely to be associated with the galaxy disk, but are not clearly interpreted as due to a vertical structure. The northern dust lanes seem to cross half the galaxy disk in projection and have no clear connection to the disk or the spiral arms. These may be more likely to be the foreground dust silhouetted against the galaxy disk.

### *2.4. Edge-on Galaxies*

In several edge-on galaxies, we can recognize dark lanes crossing the disk plane or extending vertically to the galactic plane. Examples of such lanes are seen in NGC 891, NGC 4216, and NGC 4565, although their photographs so far available are too crude to be used to learn the details. The amorphous large-scale dust lanes running across M82 are also an indication of the vertical structure in the galaxy. Nakai et al. (1987) have claimed that an outflowing molecular gas driven by the starburst activity in the central region of M82 may produce such a prominent optical feature. However, it is not clear as yet if the structure is related to the magnetic field.

## 3. Discussion

If there exists a magnetic field vertically penetrating a rotating gaseous disk associated with a more slowly rotating halo, the field lines are twisted by the differential velocity between the halo and disk. The twist then causes an acceleration of a vertical outflow of the disk gas, or a so-called "soft-jet" phenomenon takes place (Uchida and Shibata 1986). This soft jet mechanism may apply to a spiral galaxy having a large-scale vertical magnetic field. We may then expect a vertical outflow of the interstellar gas, together with which a considerable amount of dust grains are blown off from the galaxy plane toward the halo. The blown-up dust will be observed as vertically extending dark filaments obscuring background starlight of the disk and bulge stars.

The vertical filamentary structures in NGC 253 and NGC 7331 are thus interpreted as due to such a vertical flow, and may be considered as evidence for a large-sclae vertical field penetrating the disk plane. It must be stressed that the vertical structure is found only in the central regions, $R<4$ kpc, in both galaxies. This fact is also consistent with the expectation that the vertical field is conveyed toward the central region with the accreting disk gas and is amplified there (Sofue and Fujimoto 1987). In fact a molecular ring of 200″-radius ($R\sim3.3$ kpc) is present in NGC 253 (Scoville et al. 1985), and a 50″-radius ($R\sim3$ kpc) ring of molecular hydrogen is also found in NGC 7331 (Young and Scoville 1982). It must be noticed that the vertical dust filaments in both galaxies are just located at the same galactocentric distances in the molecular rings. The positional coincidence suggests that the vertical outflow is most effectively driven at the high-density gaseous rings at $R\sim3$–4 kpc, where the vertical magnetic field must be highly condensed. In this way a galaxy-scale vertical outflow is produced by the soft-jet mechanism in the central few kiloparsecs, which we call a "magnetic fountain," and a considerable amount of disk matter is blown off toward the halo. This may also explain the radio halos extending above the galactic planes of NGC 253 and NGC 7331 (Klein et al. 1983, 1984).

The velocity of vertical outflow is nearly equal to Alfvén velocity (Uchida and Shibata 1986). If the magnetic field strength is $\sim 10^5$ G in the central few kiloparsecs (Sofue and Fujimoto 1987) and the gas density in the halo at $Z \sim 1$ kpc is about $\sim 10^{-3}$ H cm$^{-3}$ (de Boer and Savage 1983), the velocity is estimated to be approximately a few hundred km s$^{-1}$. This implies that the accelerated gas in the fountain reaches a few kiloparsecs height from the galactic plane within a time scale of $\sim 10^7$ yr. Although the final trajectory of the blown-up gas is not known, we may postulate that the gas will fall back to the galactic plane in a shorter time compared to the galaxy evolution time. Since the angular momentum of the disk gas is transferred to the halo via the twisted magnetic field (Uchida and Shibata 1986), the blown-up gas will come back to the disk at a larger galactocentric distance than its original position. The fountain mechanism which transfer the angular momentum from the central region to the outer region may contribute to the galaxy-scale mixing of heavy elements (e.g., Pagel 1987; Tinsley and Larson 1978), and could explain why the heavy element abundance in the outer region ($R \sim 10$ kpc) is as high as one half that in the central few kiloparsecs (Mezger et al. 1979; Henkel et al. 1982) despite the fact that the star formation rate in the central region must have been much higher than in the outer region.

In a more central region of $R < 1$ kpc of NGC 253 a high-density condensation of molecular gas has been observed (Scoville et al. 1985), and is interpreted as due to the galactic shock deceleration of the disk gas by a barred potential near the center. In such a high-density region, the vertical magnetic field must be tightly condensed, and will be deeply coupled with the ejection phenomenon in the nuclear disk. In fact a mass ejection has been observed from the center of NGC 253 (Ulrich 1978; Turner 1985), which could be attributed to a magnetic jet acceleration. A large-scale ejection of dust and molecular gas from the central region ($R < 500$ pc) of galaxies has been also observed in some other galaxies like M82 (Lynds and Sandage 1963; Nakai et al. 1987) and NGC 1808 (Véron-Cetty and Véron 1985). Although the magnetic fountain mechanism seems promising as a cause of the vertical structures in a halo, there has been no direct evidence of a magnetic field except for our Galaxy center. Observations of the vertical component of the magnetic field in spiral galaxies, in particular in the central regions, are desired to clarify whether a vertical field condensed to the central regions is really related to the central activity.

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