THE ASTRONOMICAL JOURNAL VOLUME 107, NUMBER 3 MARCH 1994

A POLAR-NUCLEUS DARK LANE IN THE BARRED SPIRAL M83: THREE-DIMENSIONAL ACCRETION IN THE NUCLEUS

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Received 1993 May 18; received 1993 August 31

ABSTRACT

The central region of the barred spiral galaxy M83 reveals a polar-nucleus dust lane, which extends from the NE molecular bar and crosses the central bulge. Its SW counterpart is not visible, being hidden behind the bulge. This asymmetry, in spite of the galaxy's face-on orientation and the symmetric bar structure in the CO line emission, indicates that the dark lane is an off-plane structure. Such a "polar-nucleus" structure can be formed by a noncoplanar, three-dimensional accretion in a warped disk.

1. INTRODUCTION

M83 (NCC 5236) is a typical barred spiral galaxy of SBc type, rich in gas and dust, with an almost face-on orientation. Optical photographs show prominent dark lanes along the bar (Fig. 1) (Plate 81), and, since the bulge size is small, the shocked gaseous lanes can be traced even near the central region. For its typical characteristics as a barred spiral, various theoretical simulations of bar-shock accretion have modeled this galaxy (e.g., Sørensen *et al.* 1976; Huntley *et al.* 1978).

In this paper, we report on an evidence for an off-plane, dense dust lane in the polar region of the nucleus, and discuss the implication of a three-dimensional accretion of bar-shocked interstellar gas in the central region.

2. POLAR-NUCLEUS DUST LANE

A photographic plate in B band was taken with the Cassegrain camera of the 2.5 m duPont telescope at Las Campanas Observatory. It was exposed on 103a-O emulsion through a Wratten 2C filter for 30 min, and is shown in Fig. 1. The bar-shocked dark lanes are clearly seen along the leading edges of the bar, which extends in the NE–SW direction. The central bulge is seen as the bright, round component near the center, and the dark lanes reach the bulge from NE and SW.

The central region of M83 is enlarged in Fig. 2(a), (Plate 82) and an unsharp-masked image of the same field is shown in Fig. 2(b). The cross in Fig. 3(a) (Plate 83) marks the position of the near-IR nucleus (Gallais *et al.* 1991). The most prominent feature found in Fig. 2(b) is the dense dust lane across the central bulge, which runs in the north–south direction. This dark lane is a smooth and bent extension of the dark lane along the leading edge of the NE bar. On the other hand, the dark lane running along the SW bar apparently stops near the southern edge of the central bulge, and cannot be seen across the central region. Although the dark lanes in the outer-main bar are symmetrically developed, their central parts show significant asymmetry. Note that the galaxy is nearly face-on with the inclination angle of $i=24°$ (Comte 1981).

We may consider the following two possibilities for this apparent asymmetry of the dark lane.

(a) The dark lanes are coplanar features, but the southern lane does not extend toward the nuclear region, and stops near the edge of the bulge, having a physically asymmetric structure.

(b) The dark lanes are symmetric with respect to the nucleus, but the dark lane coming from the NE bar is on the near side to us with respect to the nucleus, while the one from the SW bar runs behind the bulge. Hence, a polar, circum-nucleus band is composed of the dark lanes. In fact, Fig. 2(b) reminds us of the dark band around the elliptical galaxy NGC 5128, which is suggested to be a circum-galactic interstellar gas (e.g., Sandage 1961).

In order to clarify which interpretation is more reasonable, we refer to molecular line observations. In Fig. 3(a) we superpose a CO line intensity map obtained with the Nobeyama mm Array with an angular resolution of $12'' \times 6''$ (Handa *et al.* 1993; Ishizuki 1993) on the unsharp-masked B band image. This CO map, as well as the one obtained with the 45 m telescope at an angular resolution of 16″ (Handa *et al.* 1990), shows that the central molecular bar is symmetric with respect to the center of the galaxy. This implies that an equal amount of molecular gas, and therefore dust, is present in the NE and SW regions near the center. This fact immediately denies possibility (a), and hence, we may conclude that possibility (b) is more reasonable.

Hereafter we call this structure a "polar-nucleus (polar-bulge) dust lane," and illustrate its possible orientation in Fig. 4 schematically. If the lane consists of a circumnuclear circle of radius $\sim 8''$ [140 pc for a distance of 3.7 Mpc (de Vaucouleurs 1979)], about equal to the radius of the opti-

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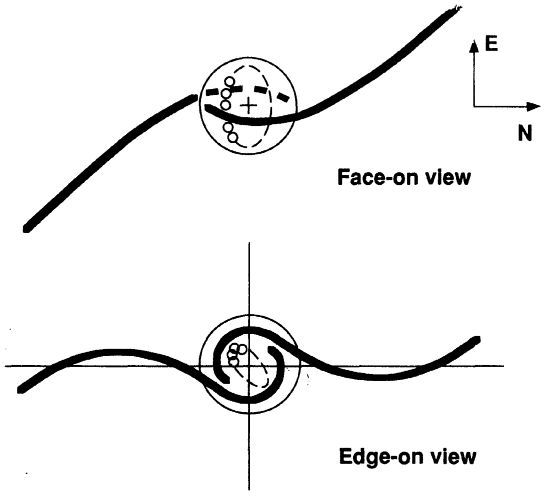

FIG. 4. Schematic illustration of the polar-nuclear (polar-bulge) dust lanes (thick lines) and the circumnuclear ring of active star formation (small circles).

cal bulge as indicated in Fig. 4 [see also Fig. 3(a)], its plane must be tilted from the galactic plane by about 70°.

Figure 3(b) shows a velocity field of CO emission which was produced using channel maps obtained by Ishizuki (1993). This map, as well as the one obtained with the 45 m telescope (Handa *et al.* 1990), shows a significant deviation from a normal circular rotation: if the rotation were circular, the isovelocity lines should run perpendicularly to the node, opening toward NW and SE directions as they leave from the nodal line. The northern part of the polar dark lane shows a positive excess, while the southern CO emission part shows negative excess which will be associated with the hidden (invisible) dark lane behind the bulge. This velocity anomaly can be understood if the polar dark lane is accreting toward the nucleus at an inward velocity of a few tens of km s^{-1}: The northern dark lane, which is in the near side of the bulge, is moving away from us with positive velocity in addition to the rotation, and the southern lane (invisible behind the bulge) is approaching us with negative velocity (plus rotation). Namely, the circumnuclear band of dark lanes as illustrated in Fig. 4 is contracting in addition to rotating.

3. DISCUSSION

3.1 Relation to the Nucleus

Gallais *et al.* (1991) made imaging observations with subarcsecond resolution at *J*, *H*, and *K* band, and detected a bright compact source which is surrounded by an arclike structure in the southwest. From brightness and position on the two color $(J-H)$ vs $(H-K)$ diagram, they identified this as the nucleus of the galaxy. We measured its position by referring to knot #6 on their Fig. 1. Thereby, we assumed that their knot #6 is the IR counterpart to the optical knot as marked B in Fig. 5 (Plate 84), which is the brightest optical knot in the western side of the polar dark lane. Knot B (and therefore IR-knot #6) coincides with the 6 cm radio continuum peak (Cowan & Branch 1985; Condon *et al.* 1982), which is, however, shifted by approximately 2 $(\pm 1)''$ ($\sim$35 pc) east to the optical knot. We also stress that these sources show an excellent correlation with the 10 μm IR emission (Telesco 1988), which suggests that knot B is an active star forming region containing hot dust.

The optical image of the nuclear region is apparently divided into two bright regions by the heavy dust lane (polar-nuclear lane), and comprises many optical knots. There is no prominent knot in the *B* band that can be identified as the nucleus of the galaxy, and this is the reason why M83 is classified as an amorphous nucleus galaxy by Sersic & Pastoriza (1967). However, by a detailed inspection of the *B* band image, we could identify an optical knot as marked K in Fig. 5 with the position of the IR nucleus (Appendix and Table 2). Radio continuum maps at 6 cm, as superposed on Fig. 3(a), also indicate no particular source at the near-IR nucleus (Cowan & Branch 1985; Condon *et al.* 1982).

The obtained positions of the nucleus are listed in Table 1, and the IR nucleus is marked in Fig. 3(a) by a cross. The error in the here-determined position of the IR nucleus [IR knot #1 of Gallais *et al.* (1991)] is $\pm 1\overset{''}{.}5$. Table 1 also lists peak positions of the CO line emission (Ishizuki 1993) and radio continuum at 6 cm (Condon *et al.* 1982). Since CO emission is extended, its peak position is estimated to have an error of $\pm 3''$, although the absolute positioning in the CO line map [Fig. 3(a)] from the Nobeyama mm-wave Array is better than $\pm 1''$. As is readily seen in Fig. 3(a), the near-IR nucleus is apparently deviated from the approximate center of the distributions

TABLE 1. Position of the nucleus at various wavelengths.

Object	R.A.	Dec. (1950)	Notes
IR nucleus	13h 34m 11.61(±0.11)s	$-29°36'40(\pm1.5)''$	Gallais et al. (1991); =identified with optical knot K
Hα peak	13h 34m 11.55(±0.04)s	$-29°36'42.2(\pm0.4)''$	Rumstay and Kaufman (1983)
Peak of CO	13h 34m 11.4(±0.2)s	$-29°36'37(\pm3)''$	Ishizuki (1993); extended (∼ kinematical center)
Radio peak	13h 34m 11.10(±0.01)s	$-29°36'35.2(\pm0.3)''$	Condon et al. (1982); 6 cm (may be not the nucleus)

TABLE 2. Positions of bright knots in the nuclear region of M83 and of reference stars.†

Object	R.A.	Dec.	Notes
Knot A	13h 34m 10.55(±0.11)s	−29°36′38.4(±1.5)″	
B	10.88s	35.1	knot #6 in Gallais *et al.* (1991)
C	11.01s	49.2	
D	11.12s	41.9	knot #5
E	11.24s	45.2	knot #4?
F	11.27s	38.7	
G	11.29s	48.1	
H	11.37s	43.6	knot #4?
I	11.50s	40.6	knot #7
J	11.60s	46.0	knot #3
K	11.67s	38.7	knot #1 in Gallais *et al.* (1991); the nucleus
L	11.68s	44.9	
M	11.68s	41.1	
N	11.74s	46.5	knot #2
O	11.89s	42.1	
Star 1	13h 34m 09.75(±0.04)s	−29°36′09.9(±0.6)″	
2	34m 12.62s	36′56.9	
3	34m 13.97s	36′23.8	
4	34m 14.13s	35′59.3	
5	34m 14.83s	36′59.2	
6	33m 46.53s	38′00.5	
7	33m 58.78s	38′36.1	
8	34m 10.33s	32′26.3	
9	34m 27.94s	35′31.8	
10	34m 28.52s	39′50.7	

†Error in positions are 1.″5 for knots, and 0.″6 for stars in both coordinates. Knots A to O and stars 1 to 6 are indicated in Fig. 5, and stars 6 to 10 in Fig. 1.

of radio continuum, molecular gas, as well as from the dynamical center (Ishizuki 1993), toward the NE by about 3″ (50 pc).

3.2 Circumnuclear Ring of Star Forming Regions

Gallais *et al.* (1991) suggested that a "near-IR arc" (their Fig. 3) is composed of a circumnuclear ring (or an ellipse) of active star forming regions. The ring can be identified with optical knots aligned along the SW edge of the bright region in Fig. 2(b), part of which is obscured by the dark lane. This star forming ring is asymmetric with respect to the nucleus, and its NE counterpart is not visible even in the near IR. Such an apparent asymmetry could be explained if the ring is tilted with respect to its node running at around PA$\simeq$130° (approximately perpendicular to the bar). Such a tilted ring (ellipse) could be produced, if star formation took place in a dust lane (molecular gas band) which had accreted in the past in a similar manner to the present polar nuclear dust lane.

3.3 Three-Dimensional Accretion in the Nuclei

Various theoretical studies have been made of accretion processes of interstellar gas in a barred spiral galaxy (Sørensen *et al.* 1976; Huntley *et al.* 1978; Fukunaga & Tosa 1991). Along this guide line, efforts have been devoted to explain the feeding mechanism of AGN through bar-shocked accretion onto the nucleus (e.g., Noguchi 1988). In these models, however, simulations have been made in a two-dimensional scheme under a restricted condition that the interstellar gas is present in a flat galactic plane. Namely, if the gas is accreted toward the center, its flow inevitably encounters the central region, but no way is allowed for the gas to escape from the disk plane. Such a restricted condition might result in an apparently efficient, and therefore, artificial accretion to the nucleus.

If we take into account three-dimensional structures near the nucleus, the efficiency of accretion to the nucleus might be reduced because of the increase in the degree of freedom in the z direction. In actual galaxies, galactic disks are known to be hardly coplanar, but are more or less warped and corrugated. This is because the majority of galaxies are not isolated, but are interacting. Warping and corrugation occurs easily by gravitational disturbances by nearby galaxies as well as by interaction with the intergalactic gas. In fact, observations have shown that the nodal line of the H I velocity field of M83 is significantly deviated (rotated) from a coplanar disk and that the H I disk is largely warped (Rogstad *et al.* 1974). The velocity field of the inner disk of M83 shows, also, deviation from a coplanar circular rotation [Fig. 3(b); Handa *et al.* 1990; Ishizuki 1993], and a part of such deviation could be due to a warp of the inner disk, although separation from noncircular motion such as the contraction must not be easy.

We may conjecture the following for the formation of a polar-nucleus structure. We assume that the galactic disk is not a flat plane, but is warped and corrugated in the z direction (perpendicular to the disk), which is really observed in the outer H I disk (Rogstad *et al.* 1974). In the outer-main bar, the interstellar gas suffers from a shock compression at leading edges of the bar due to interaction with the oval potential. Hence, the azimuthal orbital angular momentum of the gas is lost, and the gas is accreted toward the center. However, the angular momentum due to the motion perpendicular to the plane remains invariant during the accretion, since no shock occurs in the z direction. Finally, this angular momentum becomes dominant near the nucleus, and produces a polar-nuclear ring of accreting gas.

We stress that such three-dimensional accretion is more realistic, and, if we take this into account, theoretical results so far obtained by two-dimensional simulations would be significantly changed in the sense that efficiency of accretion to the nucleus is reduced.

APPENDIX

In Fig. 5 we identified optical (B band) knots in the central bulge of M83, and indicated them by A to O. We measured their positions by referring to stars 1 to 5 in Fig. 5 (Plate 84), whose positions were measured by referring to SAO stars around M83 (stars 6 to 10 in Fig. 1). Coordinates of the knots and stars are given in Table 2.

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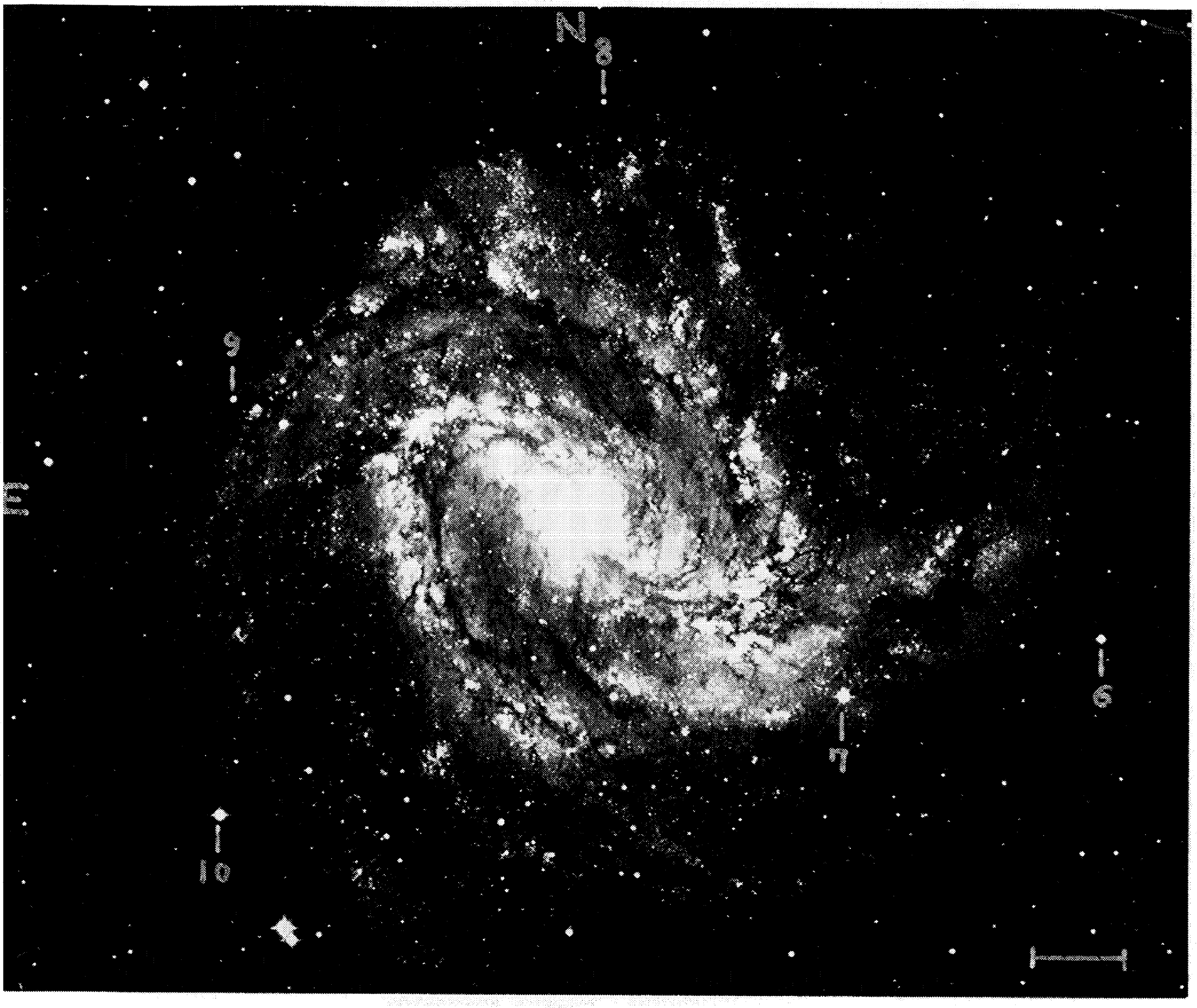

FIG. 1. A *B* band image of M83. The line at the bottom right corner indicates 1′. Positions of stars 6 to 10 are listed in Table 5.

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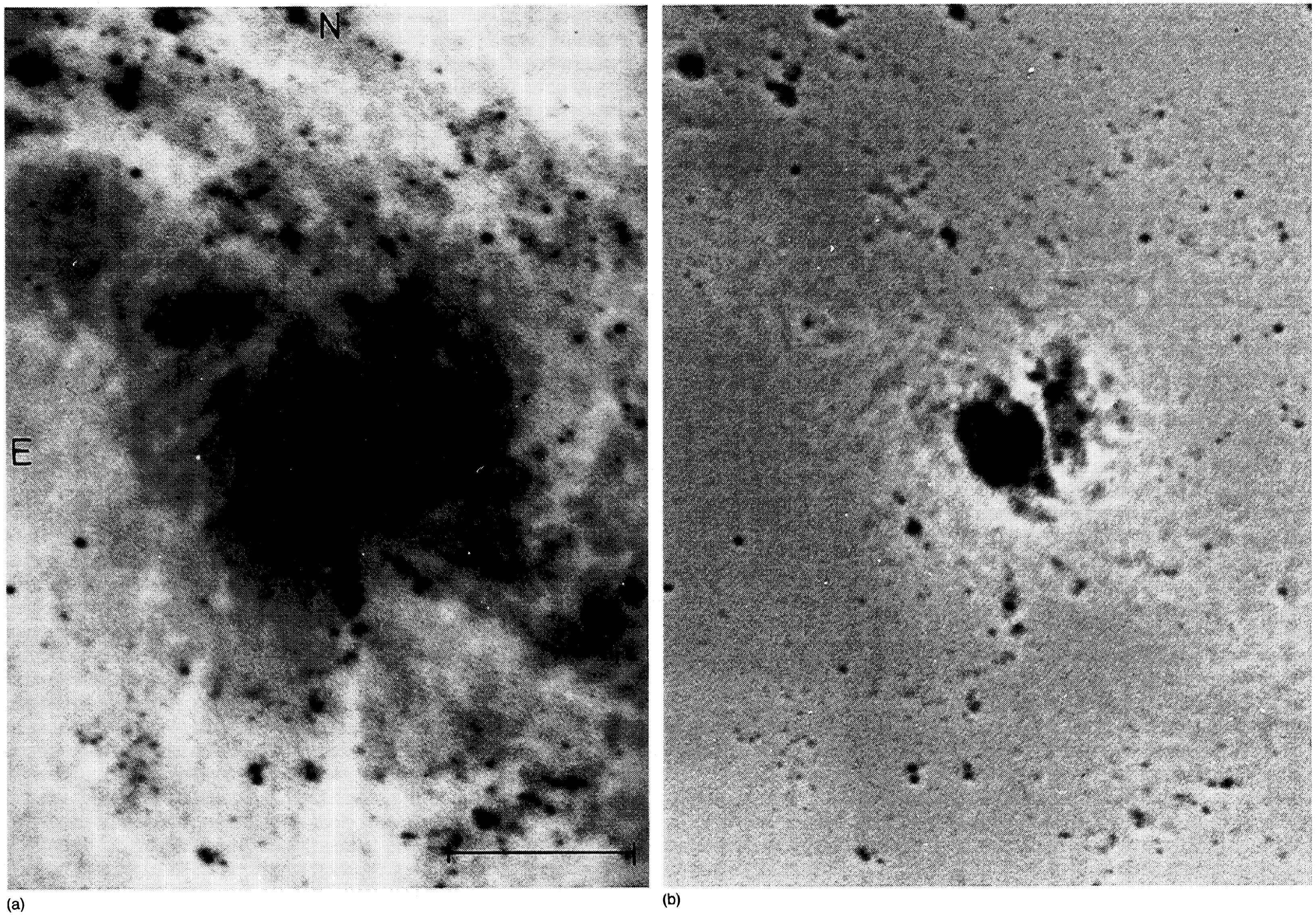

FIG. 2. (a) Left panel: The central region of M83 in *B* band. The bar indicates 30″. (b) Right panel: The same field as (a), but the image has been contrast-enhanced by unsharp masking technique. Note the straight dark lane which crosses the bulge from the north to south. The galaxy is nearly face on (i=24°).

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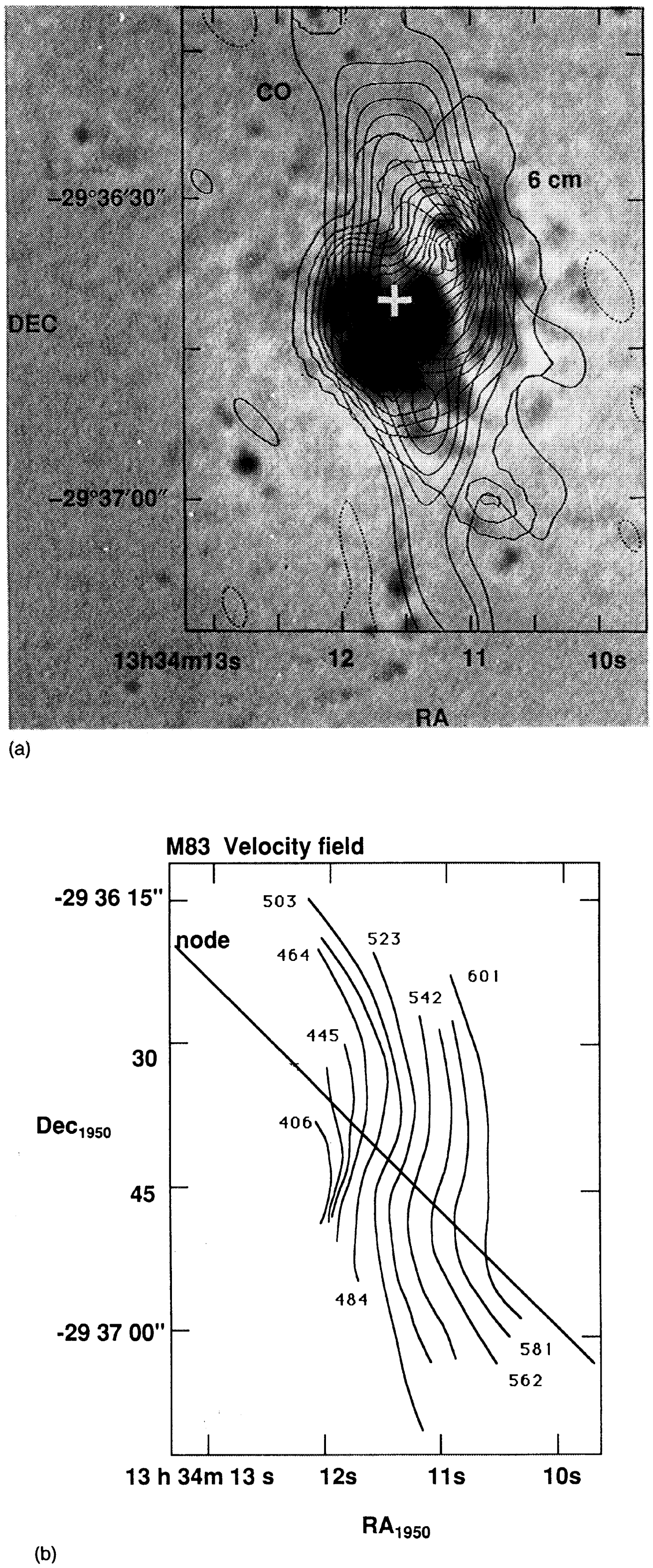

FIG. 3. (a) Superposition of contour maps of the CO line intensity (Ishizuki *et al.* 1993) and 6 cm radio continuum (Cowan & Branch 1985) on the same photograph as Fig. 2(b). The cross indicates the position of the IR nucleus (Gallais *et al.* 1991). (b) CO line velocity field for the same area as in (a), as derived from channel maps presented by Ishizuki (1993). Contour numbers are in km s^{-1}. The straight line shows a nodal line of the overall optical disk.

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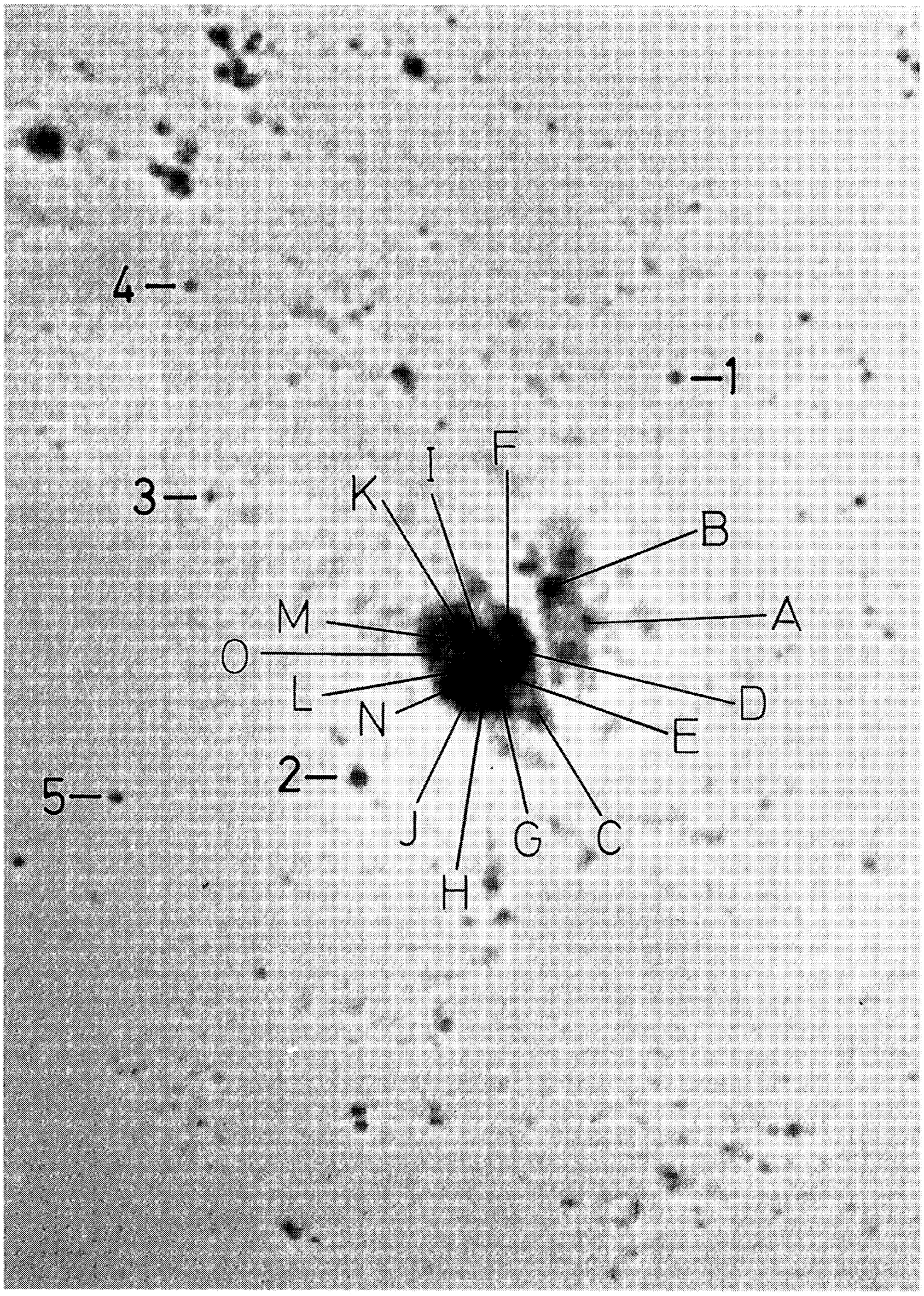

FIG. 5. Optical knots in *B* band image. Their positions are given in Table 5 together with those for reference stars 1 to 5.

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