

THE DISTRIBUTION AND KINEMATICS OF H I IN THE ACTIVE ELLIPTICAL GALAXY NGC 1052

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Received 2 December 1985

ABSTRACT

The H I distribution in the active elliptical galaxy NGC 1052 has been mapped at a resolution of 1 arcmin with the VLA. The H I structure is about three times the size of the optical galaxy and is roughly perpendicular to its major axis. The H I has a circular velocity of ~ 200 km/s, roughly constant with radius; the mass of the galaxy is $1.5 \times 10^{11} M_{\odot}$ at a radius of 16 kpc ($D = 13.4$ Mpc), and the mass to blue luminosity ratio at this radius is $M/L_B \sim 15 M_{\odot}/L_{\odot}$. H I absorption is seen against the central radio continuum source, at both the systemic velocity and at redshifted velocities. The gas in NGC 1052, as in other ellipticals, has a rotation axis that is not aligned with the stellar rotation axis (the difference is 63°) and a mean specific angular momentum that is considerably larger than that of the stars. The H I distribution is unusually irregular. In the southwest region of the galaxy, the distribution shows what appears to be a tidal tail, suggesting that the H I may have been acquired about 10^9 years ago. The presence of dust associated with the H I and the distribution and kinematics of the H I are consistent with capture of gas from a gas-rich dwarf or spiral. In the inner regions of the galaxy ($r < 5$ kpc) the H I velocity field shows evidence of noncircular orbits and therefore possibly of a triaxial mass distribution for the galaxy. Alternatively the gas could be falling in toward the center. The redshifted absorption seen in this galaxy, and seen towards the nuclei of a few other early-type radio galaxies, suggests that the accretion of gas into the center might be a general phenomenon in radio galaxies.

1. INTRODUCTION

Although elliptical galaxies generally contain little cold gas, sensitive surveys have now turned up of order 20 galaxies with detectable amounts of H I (see the summaries by Dressel, Bania, and O'Connell 1982; Lake and Schommer 1984; and Knapp, Turner, and Cuniffe 1985). The detected galaxies represent 10% of the ellipticals that have been observed in the H I line with good sensitivity and are gas-rich with respect to the majority of ellipticals.

Even for the detected ellipticals, however, the amount of H I is small. The mean observed value of $M_{H I}/L_B$ is $\sim 0.06 M_{\odot}/L_{\odot}$, and the values of $M_{H I}$ range from a few $\times 10^5$ to $10^9 M_{\odot}$. While H I content is well correlated with morphological type, luminosity, and color in spirals, this is not the case for ellipticals, and the origin of the cold gas in these early-type galaxies remains a mystery. Possible answers involve interesting and varied astrophysical processes, including mergers and tidal accretion, an epoch of gaseous infall extended to the present time, or mass loss from evolving stars and the failure of an internal galactic wind. Since any or all of these processes may play important roles in galaxy formation and evolution generally, establishing that they

operate with some frequency in ellipticals would be of value to larger questions than those of elliptical galaxy evolution.

The investigation of these ideas requires an answer to two basic questions about the cold gas seen in some ellipticals—did the gas come from inside or outside the present-day galaxy, and when was it acquired? As a contribution to this investigation, the present paper discusses high-spatial-resolution observations made with the Very Large Array (VLA) of the H I distribution in the active emission-line elliptical NGC 1052. In addition to questions of the origin of the H I in ellipticals, our data contain information on the orbital kinematics of the H I in NGC 1052 and therefore about the structure of the galaxy. Since NGC 1052 has an active nonthermal radio source in its nucleus, our data are also of interest for the suggested relationship between the presence of cold gas and that of radio emission (e.g., Hummel, Kotanyi, and Ekers 1983).

In the next section, we summarize the known data for NGC 1052, including a description of its nuclear radio emission and the data for the other members of the NGC 1052 group. In Sec. III, we discuss the acquisition and reduction of the VLA data. The kinematics of the H I distribution are described in Sec. IV. In Sec. V, the data are discussed in

terms of the gas-origin theories mentioned above, the relationship between the radio continuum and gas is examined, and the gas-to-dust ratio is discussed. The conclusions of this paper are also given in Sec. V.

Several related aspects of the data are discussed in the Appendices. In Appendix A, we describe the H I results from the VLA for the other members of the NGC 1052 group. Strong H I absorption is seen towards the nucleus of NGC 1052; the physical parameters of the absorbing clouds are derived in Appendix B.

II. BASIC PROPERTIES OF NGC 1052

NGC 1052 is a moderately luminous galaxy of normal optical morphology of type E4. The stellar kinematics also appear to be normal (Schechter and Gunn 1979). The central regions of the galaxy are spectroscopically unusual, with bright, broad, line emission seen from the nucleus [a detailed discussion of the motions of the stars and ionized gas is given by Davies and Illingworth (1985), to whom we are indebted for the use of data before publication].

The known data for the galaxy are summarized in Table I. Much of the optical information is taken from de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter referred to as RC2), Schechter and Gunn (1979) and Davies and Illingworth (1985). There are two recent measurements of the galaxy's radial velocity. Sargent *et al.* (1977) give 1471 ± 14 km/s, while Schechter and Gunn (1979) give 1475 km/s. The mean of these values, 1473 km/s, is listed as the galaxy's velocity in Table I.

NGC 1052 is the brightest galaxy of a small group that, together with the NGC 1069 group, makes up the Cetus I cloud (de Vaucouleurs 1975). A list of galaxies possibly belonging to this group, with their heliocentric redshifts, is given in Table II. NGC 1047 was tentatively detected in the H I line by Bottinelli and Gouguenheim (1980), but our observations do not confirm this detection, so no redshift is given. Also included in Table II is an object called "Dwarf A," which was discovered on a CTIO 4 m III-aJ plate of the

TABLE II. Possible members of NGC 1052 group.

Galaxy	Type	$V_{\odot}$	Refs.
NGC 1052	E4	1473	b,c,h
NGC 1035	Sc	1229	e,f,g,i
NGC 1042	Scd	1370	a,d,e,f,i
NGC 1047	S0/a	—	e
NGC 1084	Sc	1412	a,g
NGC 988	Scd	1509	f
NGC 991	Sc	1558	a,f
NGC 1022	Sa	1503	a
NGC 1051	Sm	1300	f
A0238-06	Im	1333	f
Dwarf A	—	1369	d

$$\langle V \rangle = 1405 \pm 33$$

^aRC2.

^bSargent *et al.* 1977.

^cSchechter and Gunn 1979.

^dPresent paper.

^eBottinelli and Gouguenheim 1980.

^fFisher and Tully 1981.

^gHuchra 1984.

^hShostak 1978.

ⁱFosbury *et al.* 1978.

group taken by D. A. Hunter and Gallagher; its position is $\alpha = 02^{\text{h}}39^{\text{m}}23^{\text{s}}.8$, $\delta = -08^{\circ}08'18''$ (1950). This galaxy was detected in the H I line in our present observations, and the corresponding velocity is given in Table II. The velocity data, unweighted, give a mean group velocity of 1408 km/s and a velocity dispersion of 104 km/s. Assuming Aaronson *et al.*'s (1982) model for the infall of the Local Group towards M87 and a Hubble constant of 100 km/s/Mpc, we find $D = 13.4$ Mpc.

NGC 1052 has an active radio nucleus, whose total flux at 1.4 GHz is ~ 900 mJy. Most of the flux comes from a point source; extensions are seen on arcsecond (Wrobel 1984) and milliarcsecond (Jones, Wrobel, and Shaffer 1984) scales. The position angles of these extensions are also given in Table I.

H I emission from NGC 1052 has been previously observed by Whiteoak and Gardner (1977), Knapp, Gallagher, and Faber (1978), Fosbury *et al.* (1978), Reif, Mebold, and Goss (1978), and Bottinelli and Gouguenheim (1980). The measured H I fluxes, linewidths, and central velocities (including global H I data from the present observations) are given in Table III. Also given are the observed values of the H I mass, calculated from

$$M_{\text{H I}} = 2.36 \times 10^5 D^2 \sum S \Delta V M_{\odot}. \quad (1)$$

TABLE I. Optical and radio data for NGC 1052.

Type	E4	a
Stellar rotation axis	28°	c
Optical major-axis position angle	298°	b
Optical minor-axis position angle	28°	b
Major $\times$ minor axis, 25 ^m arcsec isophote	2'9" $\times$ 2'0"	a
Corrected apparent magnitude B_T	11.21 mag	a
Heliocentric velocity	1473 km/s	see text
Group mean heliocentric velocity	1408 km/s	see text
Distance ($H_0 = 100$ km/s/Mpc assumed)	13.4 Mpc	see text
Blue luminosity L_B	$9.2 \times 10^9 L_{\odot}$	
σ_* ($\leq 2''$)	240 km/s	b
σ_* ($2'' - 10''$)	180 km/s	b
V_* max (major axis)	110 km/s	b,c
Rotation velocity of ionized gas ($\leq 5''$)	220 km/s	b
Rotation velocity of ionized gas ($\geq 5''$)	140 km/s	b
Position angle, gas rotation axis ($\leq 3''$)	112°	b
Position angle, gas rotation axis ($5'' - 10''$)	125°–131°	b
Total flux, nuclear radio source, 1.4 GHz	900 mJy	d
Nuclear jet p.a., VLBI, 5 GHz	63° $\pm$ 5°	e
Extended structure p.a., VLA, 1.4 GHz	95° $\pm$ 3°	f
Position angle of H I bar of disk	224° $\pm$ 10°	see text
Position angle, H I rotation axis	134° $\pm$ 10°	see text

^aRC2.

^bDavies and Illingworth 1985.

^cSchechter and Gunn 1979.

^dPresent paper.

^eJones *et al.* 1984.

^fWrobel 1984.

TABLE III. Global H I observations of NGC 1052.

Flux integral (Jy km/s)	Linewidth ΔV (50)%	$V_{\odot}$ (km/s)	$M_{\text{H I}} \times 10^8$ ($M_{\odot}$)	Reference
6.4	530 $\pm$ 100	1590 $\pm$ 50	2.7	a
12.0	450 $\pm$ 50	1540 $\pm$ 40	5.1	b
9.5 (12.7)	350 $\pm$ 70	1470 $\pm$ 70	4.0 (5.4)	c
8.0	490 $\pm$ 50	1486 $\pm$ 10	3.4	d
20.0	260	1300	8.5	e
5.6 $\pm$ 0.5	440 $\pm$ 60	1478 $\pm$ 50	2.8	f

^aBottinelli and Gouguenheim 1980.

^bFosbury *et al.* 1978.

^cKnapp *et al.* 1978.

^dReif *et al.* 1978.

^eWhiteoak and Gardner 1977.

^fPresent paper.

The measured H I fluxes for NGC 1052 are rather discrepant. This can be attributed in part to two factors; first, to possible contributions by emission from the neighboring spiral NGC 1042 or from extended gas in the group, and second, to the changing effect of H I line absorption due to the increase with time of the brightness of the central continuum source (see Appendix B). An attempt to correct the data of Knapp *et al.* (1978) for the effect of absorption is described in Appendix B; the estimated corrected flux is listed in Table III. The global H I flux from the present VLA observations is also given in Table III.

The values of the mean velocity of the H I line listed in Table III show very large discrepancies. Within the considerable uncertainties, however, the mean H I velocity agrees with the optical velocity listed in Table I.

III. THE VLA OBSERVATIONS AND DATA REDUCTION

The observations were made in two sessions, on 16–18 November 1982, and 16–17 July 1983. Each session consisted of two 9 hr observing runs, with the VLA in its “D” (compact) configuration (Napier, Thompson, and Ekers 1983). The instrumental parameters are summarized in Table IV. Eighteen antennas were used for the observations. In the 6 hr around transit, the inner 18 antennas were used, and in the more extreme hour-angle ranges, the six innermost antennas were replaced with ones further out to avoid shadowing. NGC 1052 was observed in scans of 40 min duration alternating with 5 min scans on the nearby point sources 0159-117 and 0218-021 to monitor changes in gain and phase. The absolute flux scale calibration was made with respect to 3C 48, whose flux density at 1413 MHz was taken to be 15.82 Jy. To calibrate the variations of gain and phase with frequency, a strong calibration source (3C 48 or 3C 147) was observed at the beginning, middle, and end of the observing run.

NGC 1052 contains a strong central continuum source whose flux was measured to be 840 mJy, in reasonable agreement with the expected value (see Appendix B). To avoid the frequency ripple caused by the presence of the source (the Gibbs phenomenon, due to finite sampling in the lag domain), Hanning smoothing in frequency was applied to the UV data, giving an effective velocity resolution of 41.4 km/s.

The peak H I line intensity in NGC 1052 is only ~ 6 mJy/beam in our observations, while the continuum flux is 840 mJy. Very high spectral dynamic range is therefore required, and special care was taken with the subtraction of the continuum source. First, a mean continuum map was formed from the frequency channels containing no line emission. This

map was CLEANed to about the 4σ level. The “CLEAN” components were then subtracted from all of the frequency channels on the UV plane. Since there was some broadband interference (suspected to be due to crosstalk) at the shorter spacings, the UV data were clipped after continuum subtraction, with rejection of all points above 1.5 Jy.

An average map was made from all frequency channels that had been used for the original continuum map. This residual map was then subtracted from all channel maps. The resulting difference maps (hereafter called line maps) had an rms noise of ~ 1 mJy per beam. Both sets of data from 1982 and 1983 were treated the same way and combined. The line maps were CLEANed and restored with a Gaussian beam of HPBW 1 arcmin (3.9 kpc at the adopted distance of NGC 1052) and have an rms noise level of ~ 0.6 mJy/beam. The line maps are presented in Figs. 1 and 2. Figure 1 shows the area containing the group members NGC 1035, NGC 1042, Dwarf A, NGC 1047, and NGC 1052, for the velocity channels containing emission from NGC 1035, NGC 1042, and Dwarf A. Further discussion of the H I properties of these galaxies is given in Appendix A. Figure 2 shows only the area around NGC 1052, with 27 line maps between velocities of 1235 and 1773 km/s. Although the velocity resolution of these maps is ~ 40 km/s, they are spaced at the channel spacing of 20 km/s because of the rapid changes in the velocity field. There is therefore some map-to-map correlation of emission features.

The global H I velocity profile for NGC 1052 was constructed from the VLA data for comparison with single-dish results (cf. Table III). Two versions of the line profile were made; first, the profile constructed directly from the data, and second, the profile constructed with negative numbers (i.e., absorption) converted to emission (see below). Since at each velocity the area containing emission was chosen interactively from examination of the line map, channels containing no line emission were not used. These line profiles are shown in Fig. 3.

Strong absorption features can be seen at the position of the center of the galaxy on the line maps (Fig. 2) between velocities of ~ 1463 and 1691 km/s. The full velocity resolution (21 km/s) line profile observed at the center of the galaxy is shown in Fig. 4. Three absorption components are seen, at velocities of 1486 km/s (close to the galaxy's systemic velocity), and 1523 and 1646 km/s (redshifted with respect to the systemic velocity). The physical properties of these absorbing clouds are discussed in Appendix B.

Maps of the column density and intensity-weighted mean velocity of the H I emission were made as follows. The line maps were smoothed spatially to a resolution of 90 arcsec and Hanning smoothed in velocity to a resolution of 60 km/s after the negative flux values (i.e., the absorption components) were clipped. The smoothed maps were then used to determine the points to be included in the moment calculations, and points below 1 mJy (2σ) were rejected. The actual moment calculations were carried out using the full resolution data. The resulting H I column density maps are shown in Figs. 5–7. In Fig. 5, the H I map is shown with sketches of the 25^m per square arc second blue optical isophotes, the projected rotation axes of the gas and stars, and the axes of the continuum structure at arcsecond (Wrobel 1984) and milliarcsecond (Jones *et al.* 1984) resolutions. In Fig. 6 [Plate 72], the total H I map of NGC 1052 is shown superimposed on Hunter and Gallagher's 4 m plate of the galaxy. The H I contour maps for the whole field, including group

TABLE IV. Instrumental parameters for VLA observations of NGC 1052.

Observing dates	Nov. 16, 18 1982 (9, 8 hr) July 16, 17, 1983 (9, 9 hr)
Field Center (1950)	$\alpha = 02^h 38^m 37^s.4$ $\delta = -8^\circ 28' 08''.9$ 18 (1982), 23 (1983)
Total number of antennas	30
Shortest and longest spacing (m)	40, 870
Half-power of primary beam (arcmin)	60
Half-power of synthesized beam (arcsec)	60×60
Velocity of band center (heliocentric km/s)	1525
Number of frequency channels	31
Channel separation (kHz)	97.7
Velocity resolution (after Hanning smoothing)	41.4 km/s
Width of continuum channel	4.7 MHz
Rms noise in channel maps	0.6 mJy/beam
Equivalent T_b for 1.0 mJy/beam area	0.17 K

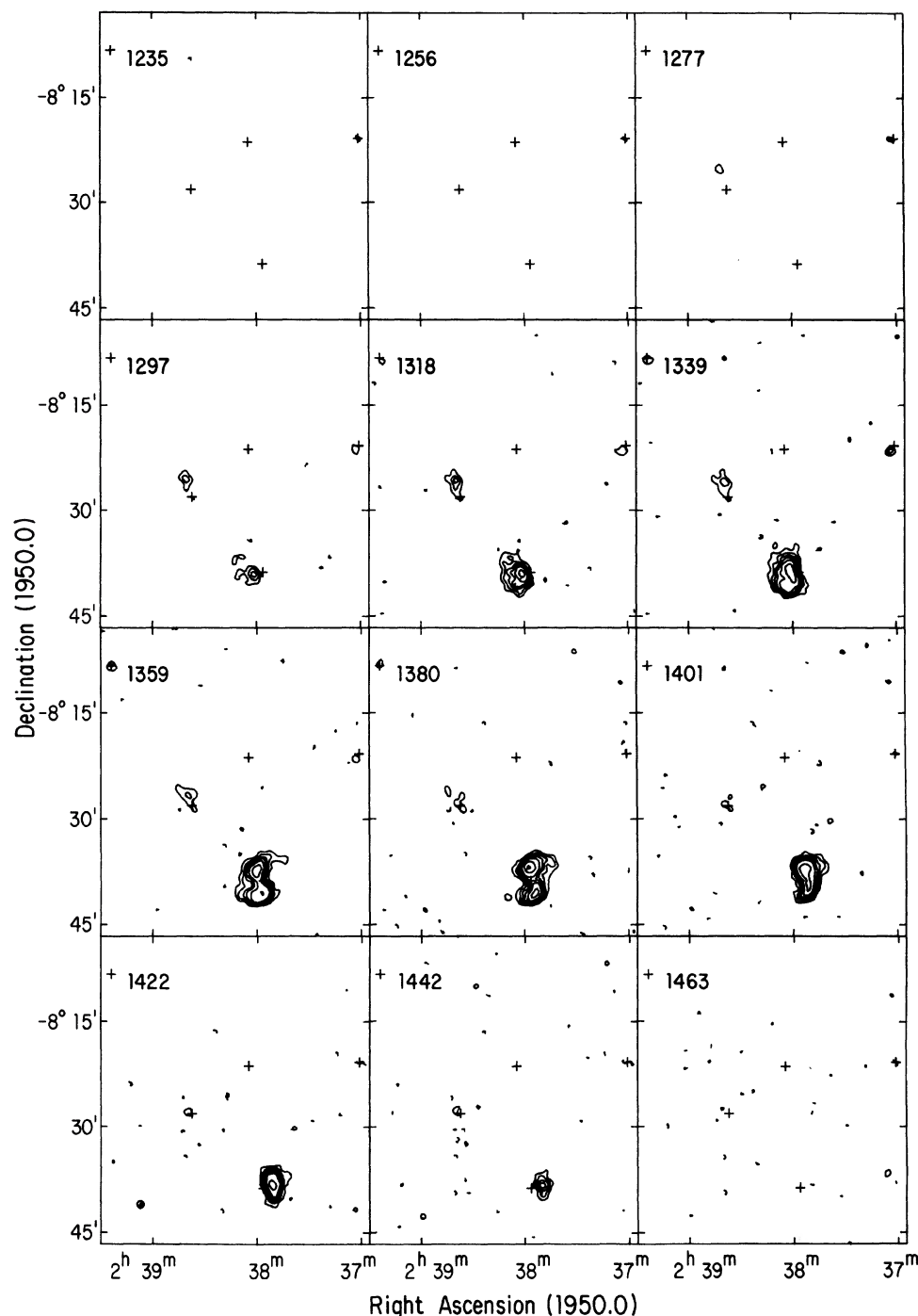


FIG. 1. Line maps of the field containing NGC 1052, NGC 1042, NGC 1047, NGC 1035, and Dwarf A. The positions of the galaxies are marked by crosses. The central velocity of each map is given in the top left-hand corner. The synthesized HPBW $60'' \times 60''$ is shown by the hatched circle. The contours are at -10.8 , -9 , -7.2 , -5.4 , -3.6 , -1.8 , 1.8 , 3.6 , 5.4 , 7.2 , 10 , 15 , and 20 mJy/beam. Negative contours are dashed. The negative contours seen at the position of NGC 1035 are due to line emission from this galaxy in the channel maps used to form the average subtracted background map.

members Dwarf A, NGC 1042, and NGC 1035, are shown superimposed on the 4 m plate of the field in Fig. 13 (Appendix A).

Because the contribution of the H I producing the absorption is missing from these maps, a second H I map and velocity field which included the effect of the H I absorption were estimated in a similar manner to that described above. First, optical-depth maps were formed for the channels containing absorption. These were then converted to emission assuming a spin temperature of 100 K and added to the original maps (in which negative values had been set to zero). The result-

ing total hydrogen map and velocity field, compared with the maps made from the uncorrected data, are shown in Figs. 7 and 8.

As can be seen from Figs. 5–7, the H I distribution is unusual in its orientation with respect to the optical image (the inner H I structure is almost aligned with the optical minor axis), in its extent (three times the Holmberg radius) and its asymmetry. Figure 7(b) suggests that the H I column density actually peaks at the center of the galaxy. The derived column density is probably still a lower limit to the true central H I column density because: (a) the optical depth of

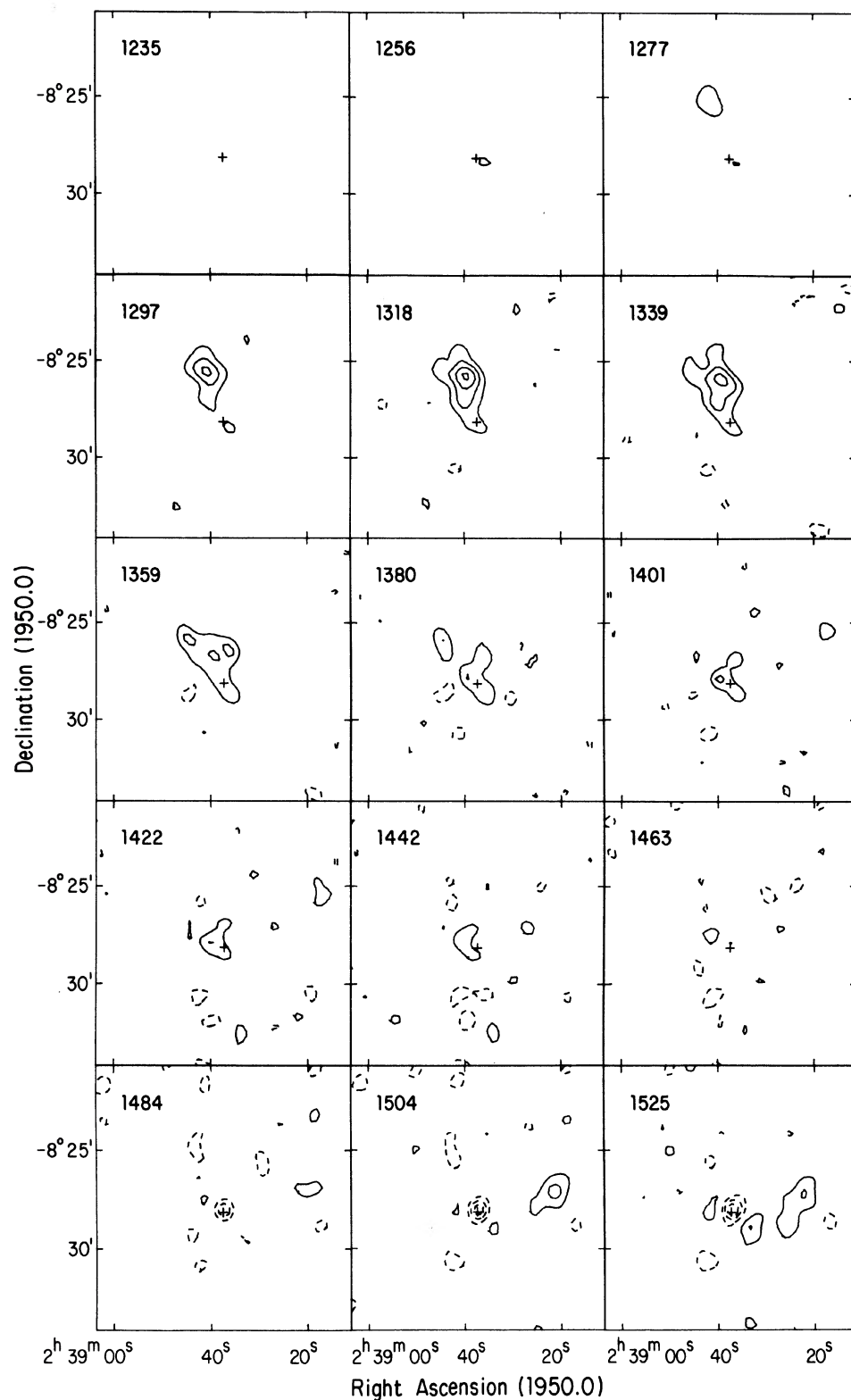


FIG. 2. Line maps of the field containing NGC 1052. The velocity resolution is 41.4 km/s and the spatial resolution, $60'' \times 60''$, is shown by the hatched circle. The contours are -10.5 , -9 , -7.5 , -6 , -4.5 , -3 , -1.5 , 1.5 , 3 , 4.5 , 6 , 10 , 14 , 18 , and 22 mJy/beam.

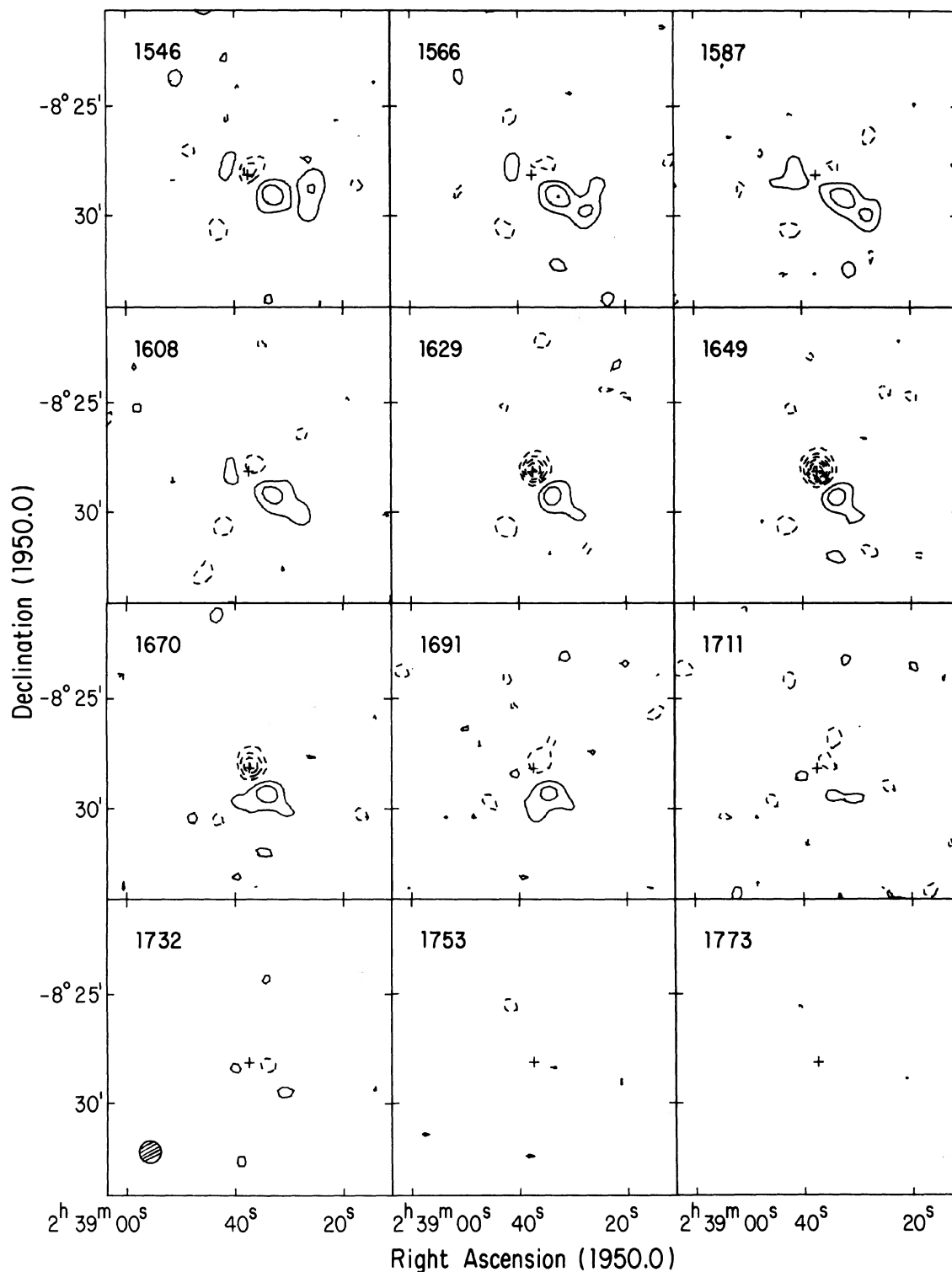


FIG. 2. (continued)

the absorption lines may have been underestimated because of the presence of H I in emission at those velocities (the continuum source has a much smaller angular size than the beam), and (b) the spin temperature of the H I could well be greater than 100 K if it is close to the central continuum

source (cf. the discussion in Appendix B). The central peaking of the H I column density suggests that there is gas physically close to the center of the elliptical.

The kinematics of the H I are discussed in detail below (Sec. IV); however, two remarks can already be made. First,

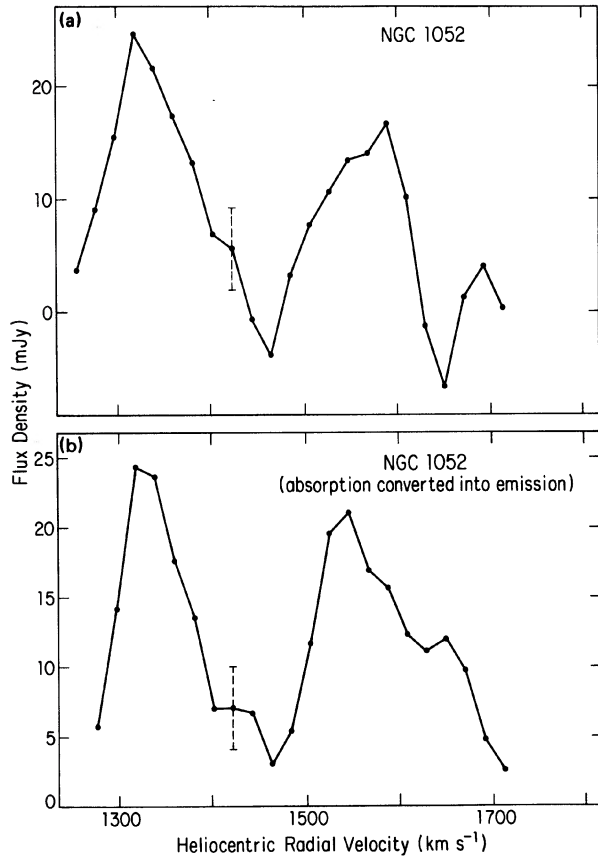


FIG. 3. Global line profiles measured for NGC 1052 with the VLA (a) with absorption clipped (b) with absorption restored (see text).

Fig. 8 shows that, when the data are corrected as described above for H I absorption, the resulting velocity contours are quite smooth. This suggests that the absorbing gas is part of the large-scale H I structure and is not due to individual clouds at anomalous velocities (falling into the center, for example). Second, a change of orientation of the isovelocity

contours can be seen right at the center of the galaxy, suggesting that the orientation of the gas orbits changes close to the center.

IV. DISTRIBUTION AND KINEMATICS OF H I IN NGC 1052

The H I seen in the direction of NGC 1052 is clearly associated with the galaxy, despite its chaotic appearance. Figures 5–7 show that in projection the H I distribution is centered on the galaxy, while the mean velocity (Table III) agrees with that of the stars. The H I radius, however, is much greater than that of the optical galaxy, and the H I structure is strongly inclined to the galaxy's major axis.

From the channel maps in Fig. 2 it appears that the gas moves rather systematically from NW to SE with increasing velocity, suggestive of a disk in rotation seen close to edge-on. Deviations from this pattern occur right in the center, however, where gas can be seen over the whole velocity range, and also in the outer parts. In the NE the disk seems to be warped, and in the W and SW a feature can be seen that looks remarkably like a tidal tail such as is seen in interacting spiral galaxies. In the SW this feature either connects up, or overlaps, with the disk. As a consequence the velocity field shown in Fig. 8, which is intensity weighted, might not reflect the real gas motions in the SW if superposition of features is occurring. Although in the channel maps there is a strong suggestion that the NE and SW parts of the disk are continuous, in discussion of the velocity amplitude, etc., we shall use the values derived from the more orderly NE part of the disk.

a) The Rotating Disk

The H I column-density distribution (Fig. 7) shows a bar or disk essentially along the galaxy's minor axis. The position angle of the gas is $224^\circ \pm 10^\circ$, making an angle of 74° with the optical major axis of the galaxy. The line of nodes in the velocity field follows more or less the peaks in the H I column-density distribution from $1'$ to $2.5'$ arc from the center. The rotation axis of the gas is therefore $134^\circ \pm 10^\circ$ over a range from 4 to 10 kpc from the center. This is in rough agreement with the rotation axis of the ionized gas in the inner 5–12 arcsec (Davies and Illingworth 1985), within the

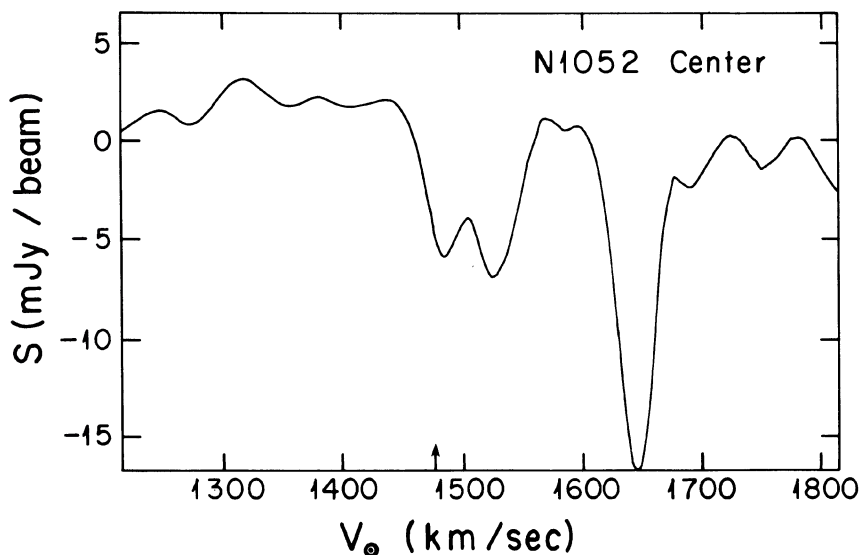


FIG. 4. Line profile for the inner 60'' of NGC 1052 observed with a velocity resolution of 20 km/s. The galaxy's systemic velocity (see text) is indicated by the arrow.

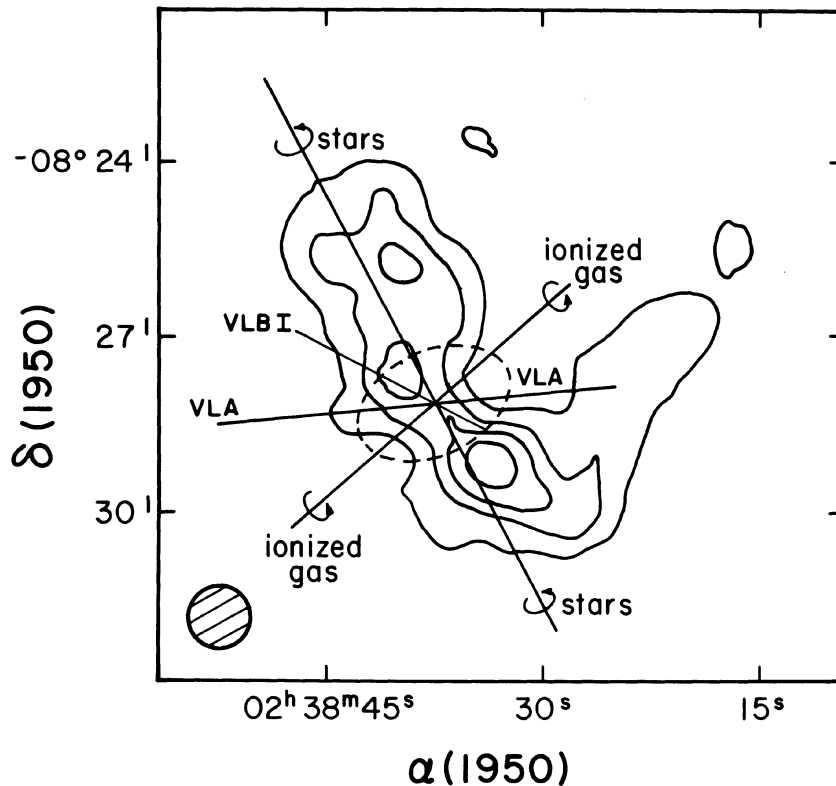


FIG. 5. Total H I map of NGC 1052. The column-density contours correspond to $0.15, 0.60, 1.07, 1.83, 2.75, 3.65 \times 10^{20} \text{ cm}^{-2}$. The half-power beamwidth is indicated by the hatched circle. The $25''$ per square arcsecond contours of the galaxy are sketched (cf. Table 1). The projected rotation axes of the stars (Schechter and Gunn 1979; Davis and Illingworth 1985) and the ionized gas (Davies and Illingworth 1985) are shown. The axes of the radio continuum features at scales of arcseconds (Wrobel 1984) (VLA) and milliarcseconds (Jones *et al.* 1984) (VLBI) are shown.

uncertainties of both position angles. The inclination of the disk cannot be determined from the current data, but the high column densities found in absorption suggest that we see it close to edge-on. Assuming that the inclination is 90° , a rotation curve can be obtained by making a position-velocity plot along the major axis of the H I. This is shown in Fig. 9(b). Some of the profiles along the major axis, at positions

of $(+1', +1')$, $(0, 0)$, $(-1', -1')$ from the center, are shown in Fig. 10. From the figures we estimate a mean velocity of $1494 \pm 10 \text{ km/s}$, and a rotation velocity of $200 \pm 20 \text{ km/s}$ at a distance of 1.4 arcmin (5.5 kpc) from the center. In the NE the rotation velocity remains constant out to 4 arcmin from the center (Fig. 8). The latter value suggests that the mass of the galaxy increases with radius out to at

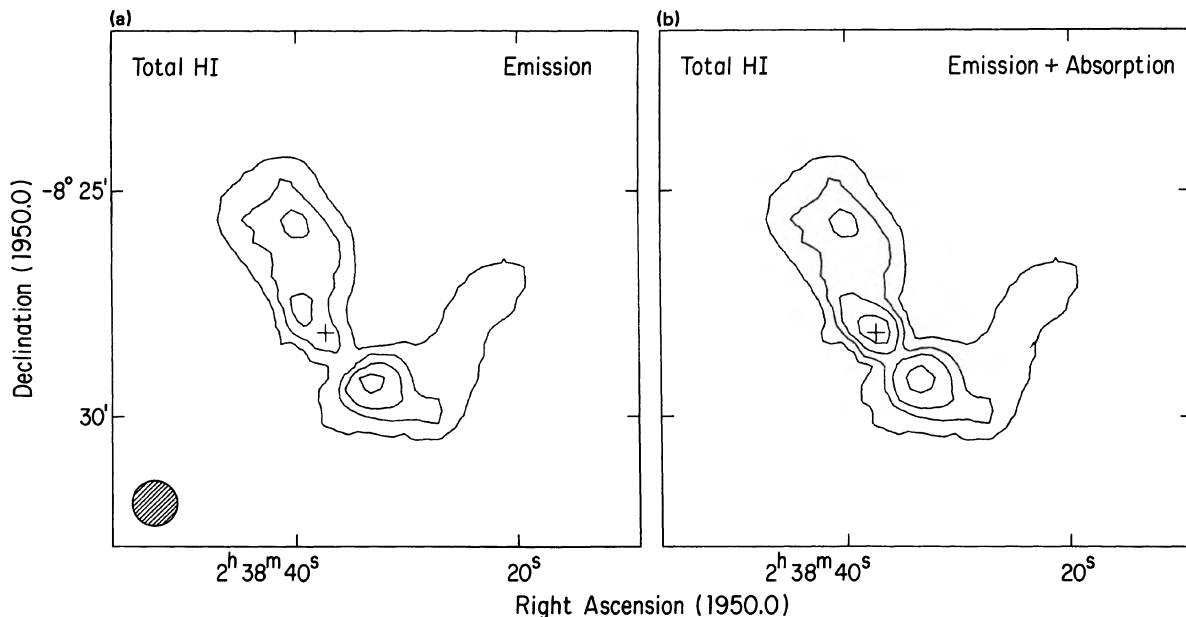


FIG. 7. Total H I map for NGC 1052 (a) with absorption components clipped (left-hand panel) and (b) with absorption components restored (right-hand panel) (see the text). The cross marks the center of the galaxy, and the contour levels are as for Fig. 5.

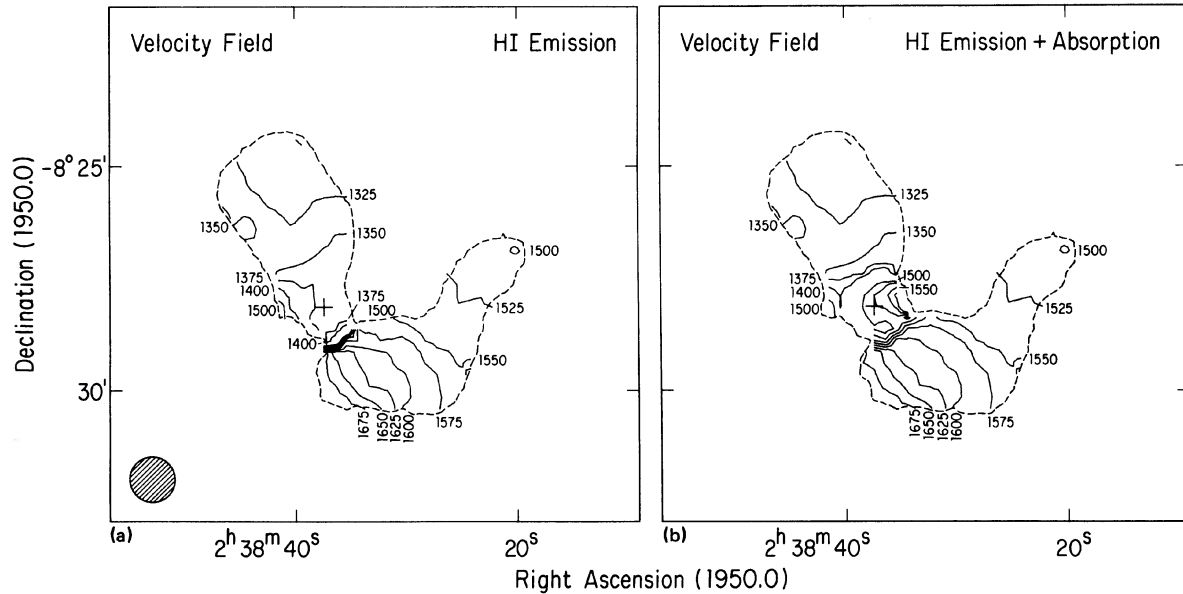


FIG. 8. Intensity-weighted H I velocity field for NGC 1052 (a) with absorption clipped (left-hand panel) and (b) with absorption restored (right-hand panel) (see the text).

least 16 kpc. At that distance the mass of the galaxy is $1.5 \times 10^{11} M_{\odot}$, giving a value of M/L_B of $15 M_{\odot}/L_{\odot}$ at this radius. The H I properties of NGC 1052 found with the VLA are summarized in Table V.

b) H I in the Center of NGC 1052

The profile in Fig. 4 and the position-velocity plot in Fig. 9(a) show emission from 1300 to 1480 km/s and absorption from 1480 to 1680 km/s in the center of NGC 1052. One would expect to see a large range of velocities in the center if the steep part of the rotation curve falls within one synthesized beam. In the present case, however, absorption is seen

against a continuum source, which has most of its flux in a VLBI component (size less than 5 milliarcsec or 0.3 pc, Jones *et al.* 1984). A rotation velocity of 190 km/s at a distance of 0.3 pc would suggest that there is a total mass of a few times $10^6 M_{\odot}$ in the central 0.3 pc. What makes this very unlikely is that the spin temperature of the H I so close to the center would be greater than 10^4 K, leading to unacceptably high column densities (Fig. 17). We are thus faced with H I at a wide range of different velocities along a very narrow line of sight. This implies that the gas is in noncircular orbits. Note that another way of getting more than one velocity along a given line of sight is to assume that the gas is in planes that have different orientations, but this does not work directly along the line of sight toward the center of the galaxy.

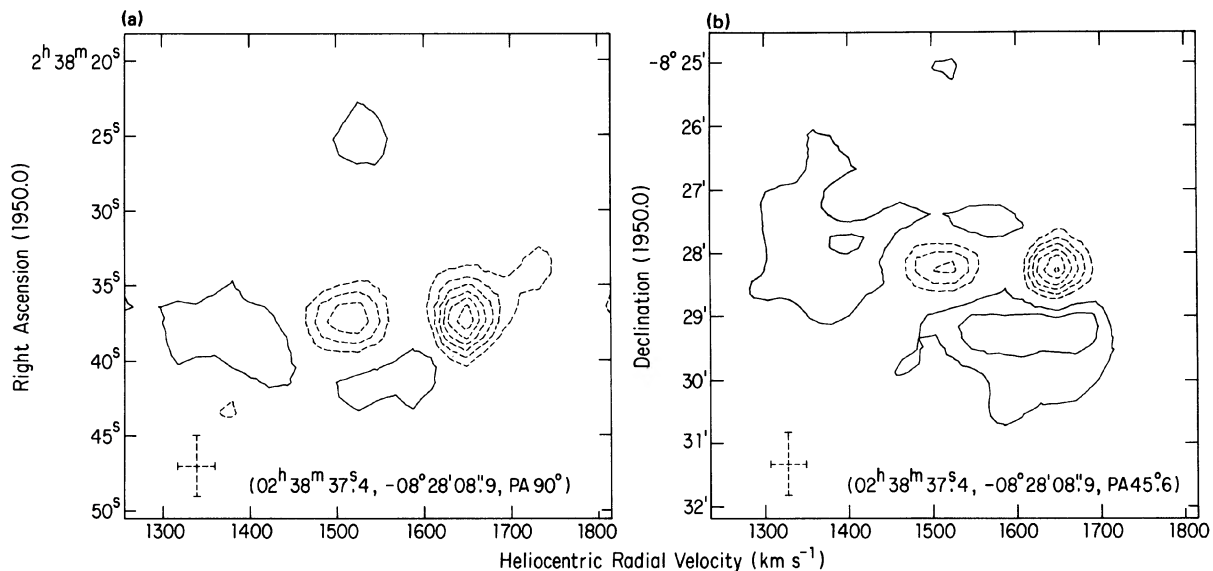


FIG. 9. Position-velocity plots along lines through the nucleus. (a) In position angle 90° (left-hand panel) and (b) in position angle 45° , the major axis of the H I distribution (right-hand panel). Contour levels are as in Fig. 2.

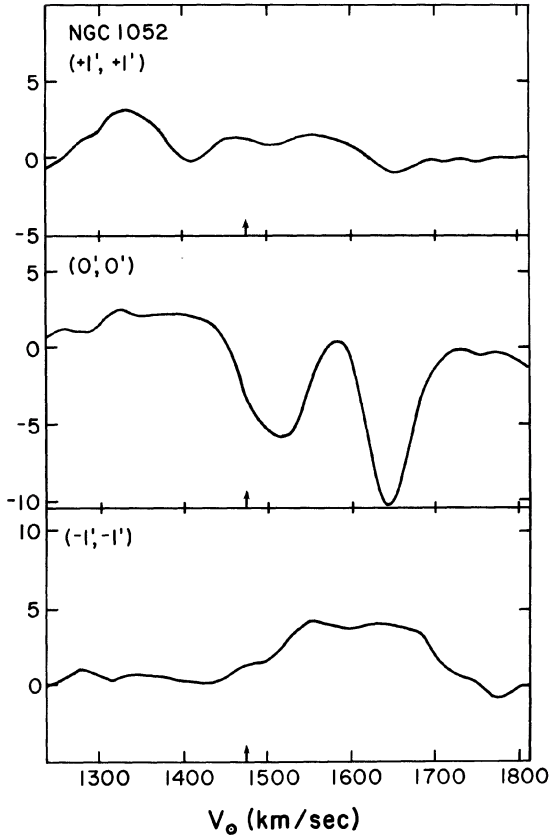


FIG. 10. Line profiles observed in the central region of NGC 1052 at 41 km/s resolution. The arrow indicates the velocity of the galaxy.

The data suggest that the gas is indeed on noncircular orbits, rather than that a few isolated clouds are falling into the center. This can most easily be seen in Fig. 11, where we show combined line maps symmetrical about the nearest channel (1484 km/s) to the systemic velocity, i.e., at $V_{\text{sys}} \pm 20$, $V_{\text{sys}} \pm 40$, etc. An extended region around the center shows both blue and redshifted emission, while at the center itself H I is seen over the whole velocity range, blueshifted in emission, and redshifted in absorption. This pattern is what one would expect to see if the gas were in elliptical orbits with the major axis of the ellipse at the proper angle to the line of

sight. A schematic diagram of such orbits is shown in Fig. 12. The orbits are viewed at an angle to their major axis. Two representative orbits are shown, and several lines of sight indicated. Along (1) blueshifted emission is seen, along (2) and (4) both redshifted and blueshifted emission is seen, along (3) redshifted absorption and blueshifted emission is seen. Along (5) redshifted emission is seen. The fact that noncircular velocities are more pronounced close to the center of the galaxy suggests that the orbital eccentricity increases towards the center of the galaxy.

Such behavior of closed stable orbits is predicted in a triaxial potential (cf. Heisler, Merritt, and Schwarzschild 1982). The eccentricity of such orbits increases with decreasing radius until the orbits are essentially line orbits along the figure rotation axis, which in the case of NGC 1052 is inclined to the plane of the sky, giving redshifted and blueshifted gas seen in the inner regions of the galaxy.

This is only one possible way of explaining the observed velocities. The quality and resolution of the data do not allow us to say for sure that the gas is indeed on stable orbits. Alternatively it might be slowly spiraling in toward the center. The question can, however, be addressed statistically; if gas is in general on elliptical orbits, there should be no preference for redshifted over blueshifted absorption. On the other hand, infalling gas obviously produces redshifted absorption. In this respect it is very interesting to note that there are now four elliptical radio galaxies with a nuclear radio point source for which good-quality interferometric absorption data exist (van der Hulst, Golisch, and Haschick 1983; Shostak *et al.* 1983; van Gorkom and Laing 1985). These four (NGC 5128, 315, 1052, and 5363) all show redshifted absorption against the central source; three show also absorption at the systemic velocity, and none shows absorption at a blueshifted velocity. The two that have also extended radio continuum emission show absorption against the more extended structure at the systemic velocity only. This suggests that the redshifted gas is actually close to the center. Although this is small number statistics, these results hint at the possibility that it might be a general phenomenon in radio galaxies that the ultimate fate of the gas is to be accreted into the center, possibly fueling the central source.

In this respect it is also interesting to compare the rotation axis of the gas with the axis of the radio source in NGC 1052. The position angle of the VLBI structure is almost perpendicular to the rotation axis of both the H I and the ionized gas (Table I, Fig. 5). The more extended radio continuum emission (Wrobel 1984) is inclined at 45° to the projected H I rotation axis. Perhaps the rotating gas collimates the radio source rather than determining its direction of ejection (cf. Kotanyi and Ekers 1979).

c) H I in the Outer Regions

The most remarkable feature of the H I in the outer regions is the tidal tail seen in the SW. Both the velocity field and the column-density distribution look very similar to tails of interacting spiral galaxies mapped in H I. Usually such tails are viewed as gas and stars pulled out of the galaxy, but for NGC 1052 we consider it more likely that it is the gas most recently captured by NGC 1052. An approximate time scale can be found from the orbital time for the gas at the largest distance from the galaxy that can still be said to be in a circular orbit. From Fig. 5 this appears to happen at about 12 kpc from the galaxy, where the orbital time is 4×10^8 yr.

TABLE V. H I properties of NGC 1052, VLA observations.

Distance	$13.4 \text{ Mpc} \times \left(\frac{100}{H_0}\right)$
FI (Jy km/s)	5.6 ± 0.5
$M_{\text{H I}} (M_\odot)$	$2.4 \pm 0.2 \times 10^8 M_\odot \times \left(\frac{100}{H_0}\right)^2$
H I radius (kpc)	$19.5 \text{ kpc} \times \left(\frac{100}{H_0}\right)$
Position angle of inner H I structure	$224^\circ \pm 10^\circ$
Central velocity (global profile) (km/s)	1480 ± 30
ΔV (global profile) (km/s)	400 ± 20
N_{H} towards nucleus	$2.5 \times 10^{20} \text{ cm}^{-2}$
N_{H} at position $(-1', -1')$	$2.6 \times 10^{20} \text{ cm}^{-2}$
Central velocity (inner 2') (km/s)	1484 ± 20
ΔV (inner 2') (km/s)	420 ± 20
H I rotation axis (inner 2')	$134^\circ \pm 10^\circ$
M/L_B at 16 kpc	$15 M_\odot/L_\odot \times \frac{H_0}{100}$

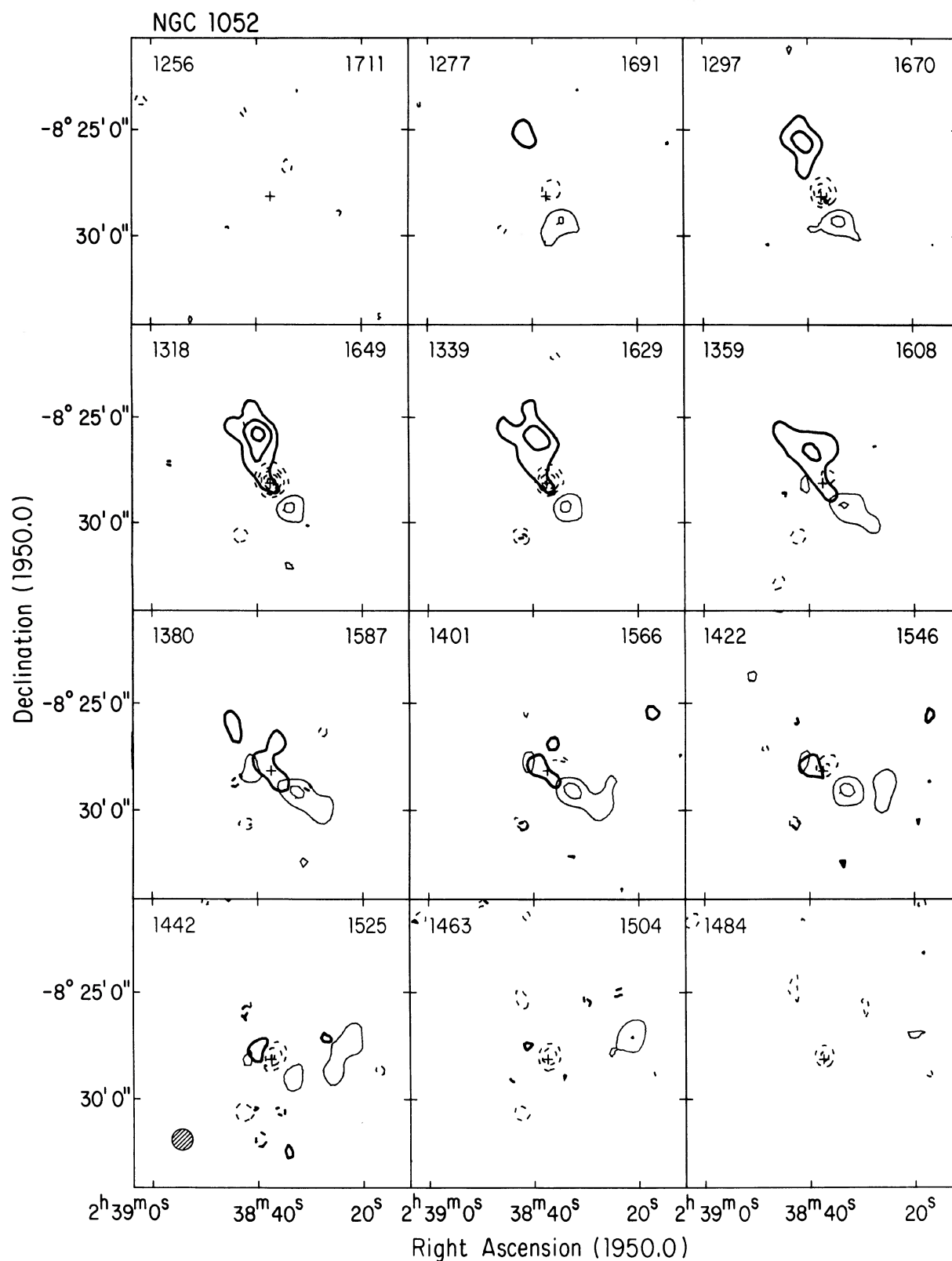


FIG. 11. Combined line maps for NGC 1052 at velocities symmetric with respect to the systemic velocity. Light line: redshifted emission. Heavy line: blueshifted emission. Dashed line: absorption.

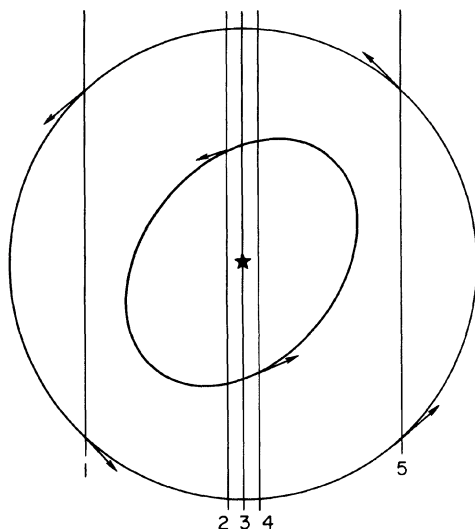


FIG. 12. Sketch of circular and elliptical orbits in NGC 1052.

This suggests that the gas was acquired $0.4\text{--}1.0 \times 10^9$ years ago.

The H I structure in the NW (Figs. 2 and 8) is actually rotating retrograde to the motions of the optical galaxy. This is consistent with the gas being on stable orbits in a rotating triaxial stellar system as shown by van Albada, Kotanyi, and Schwarzschild (1982); Fig. 5 should be compared with Fig. 2 of van Albada *et al.* (1982). Alternatively it might be showing the signs of a tidal distortion like the tail in the SW.

V. DISCUSSION AND CONCLUSIONS

a) The Origin of the Gas in NGC 1052

The present observations have revealed that the H I in NGC 1052 is unique among ellipticals studied so far with regard to extent (three times the optical radius), and asymmetrical and irregular distribution and velocity field. It does, however, resemble other ellipticals in the sense that the H I is roughly in a disk, with the rotation axis not well aligned with the stellar rotation axis and with a specific angular momentum that is much larger than that of the stars. Similar behavior of the H I is seen in NGC 4278 (Raimond *et al.* 1981) and NGC 5128 (Graham 1979; van Gorkom *et al.* 1985). NGC 1052 resembles NGC 5128 further in having a dust lane along the minor axis (Knapp *et al.* 1978; Carter *et al.* 1983).

Gallagher (1985) has made a color map of NGC 1052 in the $B - I_K$ color index (cf. Gallagher and Mould 1981) and finds a maximum reddening of ~ 0.14 mag at a distance from the nucleus of $\sim 30''$ along the northeastern minor axis. A minimum gas column density can be estimated by assuming that the cloud of gas and dust forms a screen in front of the galaxy (cf. Gallagher and Hunter 1981). Assuming that the gas-to-dust ratio is the same as that in the solar neighborhood ($N_{\text{H I}}/E_{B-\nu} = 5 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$, Savage and Mathis 1979), we find $N_{\text{H I}} > 3 \times 10^{20} \text{ cm}^{-2}$ for the disk column density in NGC 1052. This result is in reasonable agreement with the observed H I column density in the inner disk of NGC 1052. Therefore, the gas-to-dust ratio in NGC 1052 may be similar to that found in the local region of the Galaxy, a conclusion reached also by Davies and Illingworth (1985), who find a similar gas-to-dust ratio towards the nucleus of NGC 1052.

The presence of a roughly normal Galactic gas-to-dust ratio in this early-type galaxy provides a useful clue to the origin of the gas. As mentioned in the Introduction, at least three possible scenarios have been suggested for the origin of H I in ellipticals: stellar mass loss, gaseous infall extended to the present time, and mergers or tidal accretion. We shall consider each of these in turn.

The stellar mass-loss hypothesis has recently been discussed by Nulsen, Stewart, and Fabian (1984). These authors suggest that most ellipticals maintain a cooling flow as the result of stellar mass loss. If the flow becomes turbulent, angular momentum will be transported outwards as the gas flows in, which eventually might lead to the formation of cool "excretion" disks. We have a number of reasons to consider this an unlikely scenario for NGC 1052 and in fact for ellipticals in general. The problems with it are the following:

Although NGC 1052 does have an x-ray source, its total energy is only a modest $1.5 \times 10^{39} \text{ erg s}^{-1}$ in the 0.2–3.5 keV range (Helfand 1983). If this is due to thermal bremsstrahlung from hot gas, the corresponding amount of hot gas would be a few times $10^8 M_{\odot}$ (Forman, Jones, and Tucker 1985). Thus the amounts of hot and cold gas are very similar. The angular momentum of the cold gas, however, is at least a factor of 5 larger than the total angular momentum of gas shed via stellar mass loss, requiring an extraordinarily efficient angular-momentum transfer mechanism. An equally serious problem is the presence of dust. Since dust cannot survive for long in environments where the gas temperature is $> 10^6 \text{ K}$ (Draine and Salpeter 1979), it is unlikely that gas stored in a hot galactic or group corona would contain dust. As it is also unlikely that dust grains will condense in such gas as it cools due to its low density, gas accreted into a galaxy via a cooling flow (cf. Forman, Jones, and Tucker 1985) is likely to be comparatively dust-free. Finally, the misalignment of the rotation axes also poses a problem. Although it is true that different stable orbits exist in a triaxial potential, it is not *a priori* clear how gas that originates within the galaxy with a rotation axis well aligned with the stars could move outward and change its orientation of rotation by $\sim 90^\circ$ unless the galaxy has a strongly triaxial dark halo. A more general problem with the Nulsen *et al.* model is that it predicts that massive rapidly rotating ellipticals should have the largest H I content. It is, however, well established that there is little correlation between H I content and luminous mass in ellipticals (Knapp *et al.* 1985).

Similarly, the near-normal extinction properties of the interstellar medium in NGC 1052 argue against continued slow accretion of primordial gas, as does the lack of alignment between the gas and stellar major axes and the lack of any signs of a stellar disk in the galaxy.

The likeliest source of the H I in NGC 1052 is therefore in the fairly recent accretion of gas from a dwarf or spiral in the group. The amount of H I in NGC 1052 is $\sim 10\%$ of that in the nearby spiral NGC 1042 and about four times that in Dwarf A (cf. Appendix A). Thus, both of these possible sources of the gas are plausible. This hypothesis suffers, however, from the lack of an obvious donor for the gas—the H I in NGC 1042, for example, seems little disturbed, and no traces of gas were found in between the galaxies (Appendix A).

b) Conclusions

(1). The H I cloud in the elliptical galaxy NGC 1052 has been mapped at a resolution of ~ 1 arcmin using the VLA.

The H I is in a rotating disk whose projected major axis is close to perpendicular to that of the optical galaxy. The radius of the H I structure is about three times the de Vaucouleurs radius of the galaxy.

(2). The circular velocity measured in the H I disk is ~ 200 km/s and is roughly constant with radius. At a radius of 16 kpc, the mass-to-light ratio is $M/L_B = 15 M_\odot/L_\odot$.

(3). The outer H I shows structure resembling a tidal tail, suggesting that the H I was acquired $\sim 10^9$ years ago.

(4). The most likely source for the H I in NGC 1052 is tidal capture of gas from a dwarf or spiral member of the NGC 1052 group—the identity of the donor galaxy, however, is not obvious.

(5). H I absorption is seen against the central point source in the galaxy at the systemic velocity and redshifted with respect to it. The gas in the inner regions of the galaxy also shows evidence of noncircular orbits. The gas could be in highly elliptical orbits, such as would be expected in a triaxial potential; alternatively it might be falling in towards the center. The absorption at redshifted velocities seen in three other radio ellipticals suggests that infall is perhaps a rather general phenomenon in radio galaxies.

We are very grateful to R. Ekers for valuable discussions, to D. Hunter for providing the plates for the NGC 1052 group, and to R. Davies, G. Illingworth, R. Ekers, J. Wrobel, and D. Helfand for providing data before publication. This research was partly supported by NATO Grant No. RG.217/81 to E.R. and S.M.F., and by NSF Grants Nos. AST82-13292 and RII-8503097 to Princeton University, AST82-14127 to the University of Illinois, and AST82-11551 to the University of California, Santa Cruz. The National Optical Astronomy Observatories are operated by Associated Universities for Research in Astronomy, Inc., under contract with the National Science Foundation. The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

APPENDIX A: H I OBSERVATIONS OF NGC 1052 GROUP MEMBERS

Several previous observations for the global H I content of other members of the NGC 1052 group are listed in Table VI. The H I column-density map made with the VLA for the galaxies in the group is shown superimposed on Gallagher and Hunter's 4 m IIIaJ plate of the group in Fig. 13 [Plate 73]. H I emission associated with NGC 1052, 1042, 1035, and Dwarf A is seen; we find no emission associated with NGC 1047. For each of the galaxies in the field, global H I

TABLE VI. Single-dish global H I fluxes for NGC 1035 and NGC 1042.

Galaxy	FI (Jy km/s)	$(FI)_c$	ΔV (km/s)	Ref.	$M_{H I}$, ($10^8 M_\odot$)
NGC 1035	1.61	16.4	291	a	7.0
	11.4	—	200	b	4.8
	14.6	15.1	280	c	6.4
NGC 1042	38.2	44.9	125	a	19.0
	52.5	—	120	b	22.2
	44.8	53.7	119	c	22.8
	52.0	—	123	d	22.2

^a Shostak (1978).

^b Bottinelli and Gougenheim (1980).

^c Fisher and Tully (1981).

^d Fosbury *et al.* (1978).

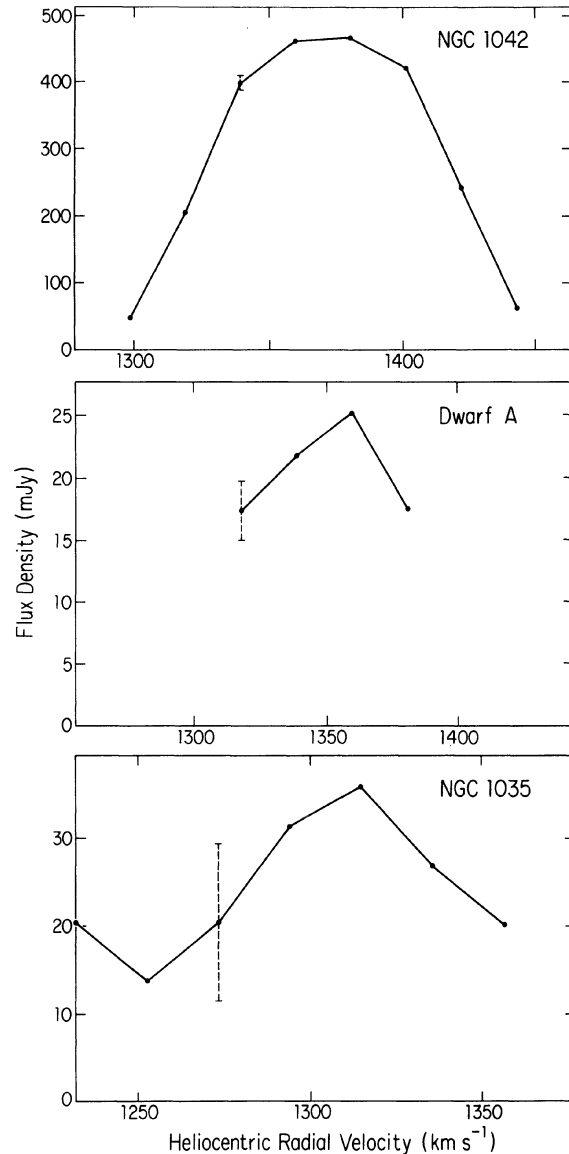


FIG. 14. Global H I profiles for NGC 1042, Dwarf A, and NGC 1035 observed with the VLA, in Jy (corrected for attenuation by the primary beam), versus heliocentric velocity.

velocity profiles were constructed (with fluxes corrected for attenuation by the primary beam) and the profiles for NGC 1042, Dwarf A, and NGC 1035 are shown in Fig. 14. The global H I fluxes are listed in Table VII.

The H I contours of NGC 1042 show a slightly asymmetric distribution in the direction of NGC 1052, possibly indicating a (former) tidal interaction between the galaxies or alternatively a warped outer disk. The global H I flux of

TABLE VII. VLA global H I fluxes for NGC 1042 and Dwarf A.

Galaxy	FI^a (Jy km/s)
NGC 1042	47.9 ± 0.5
Dwarf A	1.7 ± 0.1

^a corrected for attenuation by the primary beam.

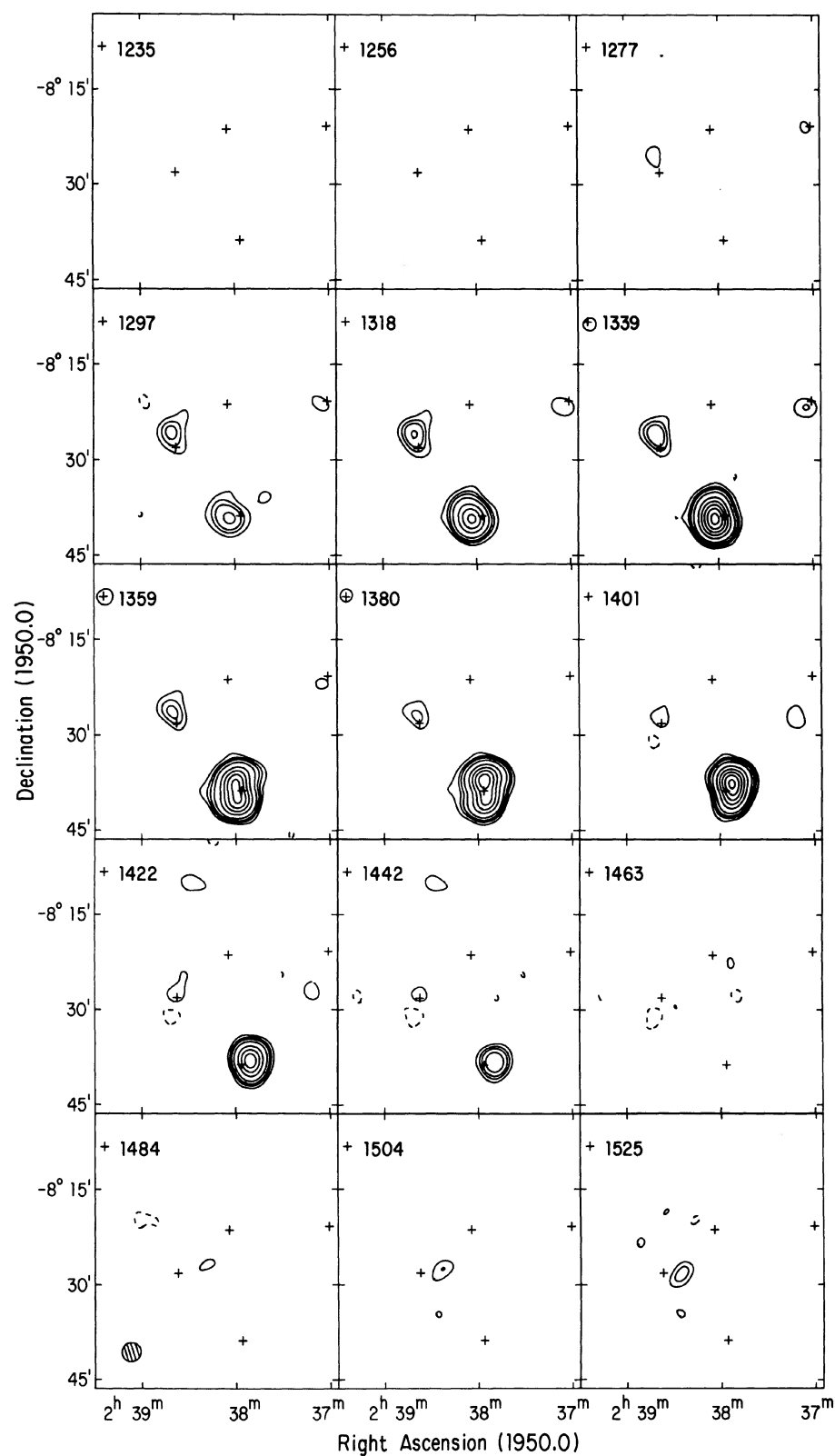


FIG. 15. Line maps of the NGC 1042/NGC 1052 field, smoothed to a spatial resolution of 3 arcmin. The contour levels are -9 , -6 , -3 , 3 , 6 , 9 , 15 , 30 , 45 , 60 , 75 , 90 mJy/beam.

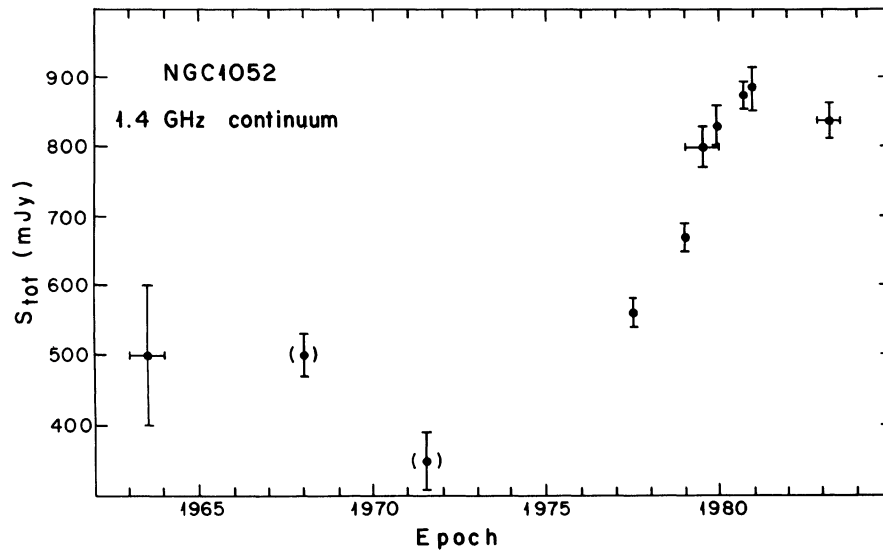


FIG. 16. Total 1.4 GHz continuum flux of NGC 1052, taken from the literature, versus time. The horizontal bars on the points indicate the time interval over which the flux observations were averaged. For the two points in parentheses, no epoch for the observation is given in the reference.

NGC 1042 agrees reasonably well with previous single-dish values (cf. Table VI), showing that our VLA observations are not missing a significant amount of flux, and therefore that there are no large-scale ($\gtrsim 10'$) resolved H I structures associated with the galaxy.

For NGC 1035, the velocity coverage of our observations extends over only half of the velocity range of the H I emission in the galaxy. NGC 1047 is not detected—the peak flux of the line tentatively detected by Bottinelli and Gougouenheim (1980) is ~ 50 mJy, in disagreement with the smaller upper limit indicated in Fig. 14. However, note (from Fig. 13) that the southwest tail of the H I in NGC 1052 points towards NGC 1047. There is presently no available radial-velocity measurement for NGC 1047.

The total H I map (Fig. 13) shows that the H I extent in NGC 1042 is not significantly larger than the optical extent of the galaxy, and its global flux measured with the VLA (Table VII) agrees with previous determinations (Table VI). In a search for extended H I in the group, the line maps were smoothed to a resolution of 3 arcmin covering the field of NGC 1042/NGC 1052. No low-level extended emission was seen at any velocity—the line maps covering the velocity range of NGC 1042 are shown in Fig. 15.

APPENDIX B: THE CENTRAL CONTINUUM SOURCE IN NGC 1052 AND PHYSICAL PARAMETERS OF THE ABSORPTION COMPONENTS

NGC 1052 is one of the minority of normal elliptical galaxies that are radio sources (e.g., Hummel 1980). The source spectrum is inverted (Heeschen 1970a; Fosbury *et al.* 1978), probably due to the presence of several components (Jones *et al.* 1984), and the source is variable at high frequencies (Heeschen 1970a; Balonek 1982). It has a core-halo structure (Heeschen 1970b) with most of the flux coming from a central source of diameter $< 0''.001$ (Cohen *et al.* 1971; Jones *et al.* 1984). Recent high-resolution 1.4 GHz maps (Wrobel 1984) show that the extended continuum emission has a double-lobed structure of projected radial extent $10''$, at a position angle of 96° ; the total flux in these extended components is ~ 120 mJy at 1.4 GHz. VLBI observations show a jet of $0''.007$ in extent at position angle 63° (Jones *et al.* 1984).

At the lowest frequency (2.7 GHz) at which Balonek (1982, 1984) monitored the source, he found that the total flux rose steadily between 1973 and 1976, essentially doubling in value, and has remained roughly constant thereafter. In Fig. 16 the total 1.4 GHz flux (core plus extended component) is plotted against time. These data are gleaned from the literature, and the time coverage is much sparser than Balonek's, but they show that the 1.4 GHz flux stayed constant at about 500 mJy until 1976, when it began to rise to 840 mJy, with a time delay of about 2 yr relative to the 2.7 GHz variations. During the time interval over which H I measurements have been made of the galaxy, the 1.4 GHz continuum flux has almost doubled.

Absorption in the H I line was first found by Shostak *et al.* (1983) in observations made with the VLA and with the Westerbork Synthesis Radio Telescope. These authors found two narrow components at 1510 and 1650 km/s, with depths corresponding to column densities of a few $\times 10^{19}$ cm $^{-2}$. The line profile seen in the direction of the nucleus of NGC 1052 in the present work is given in Fig. 4; components at 1486 km/s (close to the galaxy's velocity), 1523 km/s, and 1646 km/s are seen.

The observed parameters for each of these components are listed in Table VIII, where we give the central velocity of

TABLE VIII. Absorbing clouds in front of the NGC 1052 nucleus.

(a) VLA observations						
$V_\odot$	ΔV^a	S_{em} (mJy)	S_{obs} (mJy)	τ_0	ΔV	N_{H} (cm $^{-2}$)
1486	+13	1.8	-4.7	0.008	39	5.9×10^{19}
1523	+50	1.2	-9.6	0.013	41	1.0×10^{20}
1646	+173	0.0	-17.6	0.021	35	1.4×10^{20}
(b) 91 m observations						
$V_\odot$	T_{em} (K)	T_{obs} (K)	τ_0	ΔV	N_{H} (cm $^{-2}$)	
1486	0.020	0.009	0.020	33	1.3×10^{20}	
1523	0.024	0.009	0.027	35	1.8×10^{20}	
1646	0.021	0.003	0.003	47	3.0×10^{20}	

^a Velocity with respect to the center-of-mass velocity (1473 km/s).

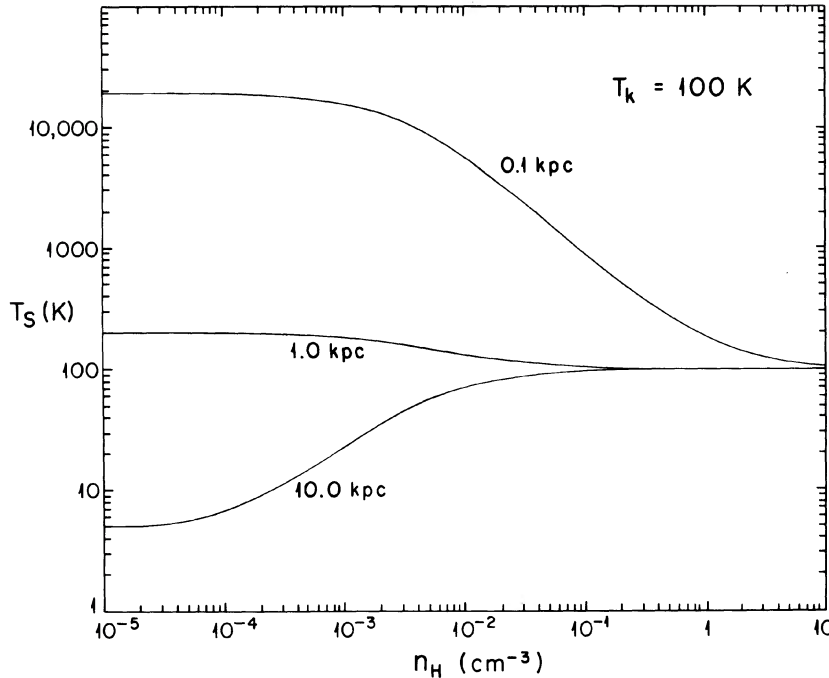


FIG. 17. H I spin temperature T_s versus density n_H for a cloud at different distances from the NGC 1052 nucleus. The assumed kinetic temperature is $T_k = 100$ K and the curves are labeled by the distance in kpc.

the feature, its redshift with respect to the galaxy's center-of-mass velocity, its maximum depth below the continuum, and its full velocity width at half-power. The line flux observed inside the $60''$ beam at velocity V is

$$S(V) = S_c [e^{-\tau(V)} - 1] + S_{em}(V),$$

where S_c is the flux of the continuum source, $\tau(V)$ is the optical depth of the absorbing feature, and S_{em} is the emission at this velocity from H I in the beam. We have estimated this last quantity by linear interpolation across the absorption dips, and it is also listed in Table VIII, as is τ_0 , the peak value of the absorption optical depth. The column density in each component is then calculated from

$$N_{H\text{I}} = 1.9 \times 10^{18} T_s \tau_0 \Delta V \text{ cm}^{-2}$$

for a Gaussian line, where ΔV is in km/s.

We have assumed $T_s = 100$ K, as is the case for H I clouds in the Galaxy. If, however, any of the clouds is very near the powerful central continuum source, its spin temperature will

be increased by the continuum radiation field (cf. Bahcall and Ekers 1969). As an illustration, the dependence of T_s on density n_H for clouds at various distances from the nucleus of NGC 1052 is shown in Fig. 17. The H I kinetic temperature is assumed to be 100 K, and the values of the H I collisional cross sections are taken from Spitzer (1978). Figure 17 shows that unless the H I is very close to the nucleus, and has a very low density, its spin temperature is little affected by the source. The H I absorption component at the galaxy's systemic velocity, which is likely to arise from gas relatively far from the nucleus, is therefore not affected by the continuum radiation. The spin temperature of the highest-redshift component could, however, be raised by the continuum source, since this cloud may be quite close to the center of the galaxy.

The cloud properties can also be estimated from the 91 m observations of Knapp *et al.* (1978). The H I profile from that paper, with the velocities of the three absorption components indicated, is shown in Fig. 18. With the wisdom of

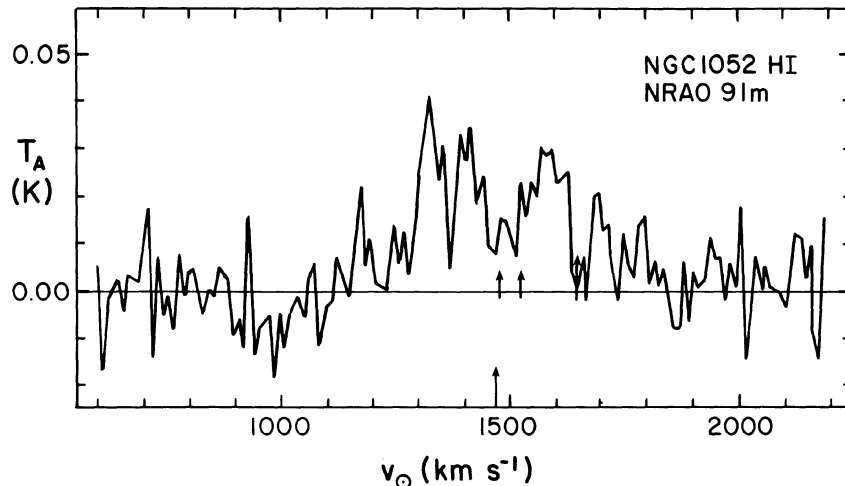


FIG. 18. Global H I profile for NGC 1052 as measured by the NRAO 91 m telescope. The galaxy's systemic velocity is indicated by the arrow on the velocity axis. The three arrows on the $T = 0$ K line are at the velocities of the three absorption features seen with the VLA (cf. Fig. 4).

hindsight, it is possible to see the absorption features in this line profile. The parameters of the clouds found from this observation are also listed in Table VIII. The continuum source strength was taken as 530 mJy (cf. Fig. 16) or 0.56 K. The total line flux from Fig. 18, corrected for these absorption dips, is the quantity listed in Table III, where NGC

1052's total H I content is given. The cloud parameters are in reasonable agreement between the two sets of measurements. The column densities of the H I clouds are similar to those seen in the Galaxy—a standard H I cloud of diameter 7 pc and density 10 cm^{-3} has a column density of $2 \times 10^{20} \text{ cm}^{-2}$.

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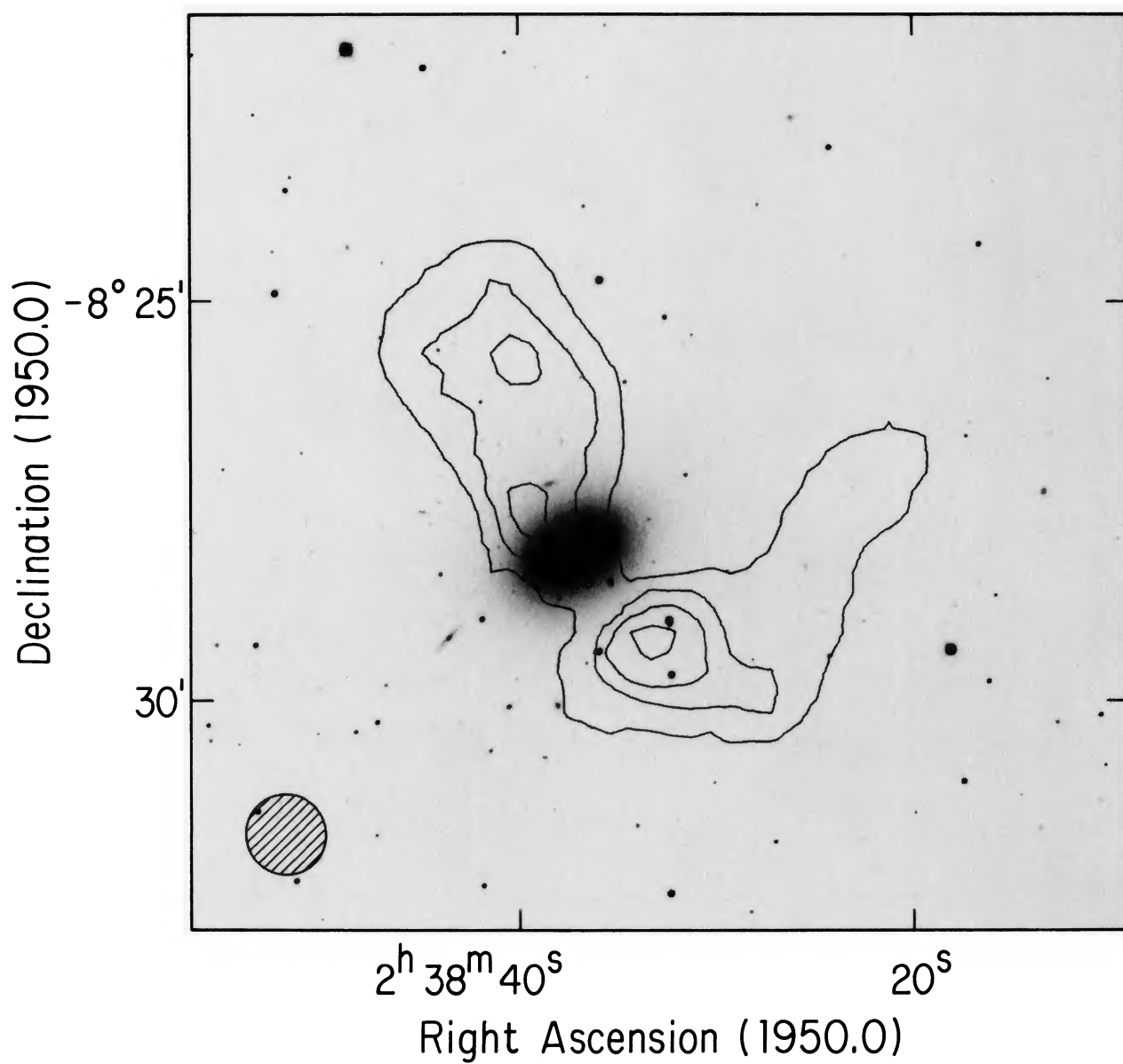


FIG. 6. Total H I map of NGC 1052 overlaid on a CTIO 4 m plate of the galaxy.

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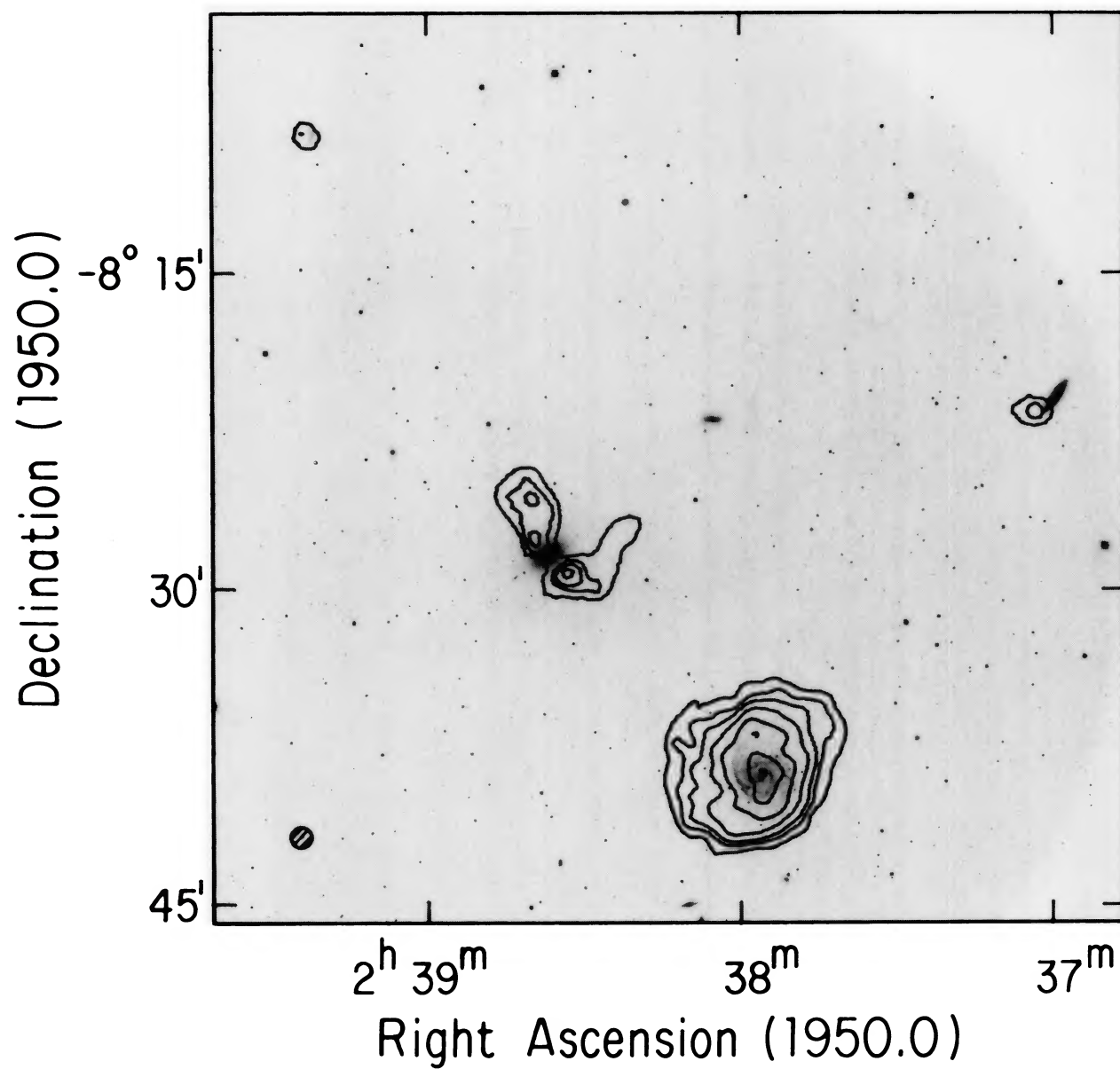


FIG. 13. Total H I map for the NGC 1052 group overlaid on a 4 m plate of the group.

van Gorkom *et al.* (see page 803)