

THE H I DISTRIBUTION AND KINEMATICS IN FOUR LOW-LUMINOSITY ELLIPTICAL GALAXIES¹

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ABSTRACT

We imaged the neutral hydrogen distribution in four low-luminosity elliptical galaxies using the VLA. *B* and *V* CCD images were obtained to determine their luminosity profiles. The brighter two of these galaxies, NGC 5666 ($M_B = -18.6$) and NGC 3265 ($M_B = -18.5$) show gapped disks, a feature typical of the H I distribution in the few bright early-type galaxies mapped to date. The gas in NGC 5666 extends to nearly 20 times the half-light radius, making it an ideal probe for the presence of dark matter. The fainter two galaxies, UGC 7354 ($M_B = -17$) and A1230+09 ($M_B = -15.6$) have centrally concentrated gas distributions, but the H I again extends to twice the Holmberg radius.

The velocity distributions in the galaxies show more or less regular rotation, NGC 5666 being remarkably regular for an elliptical galaxy. In all cases the large radial extent of the gas is compelling evidence against its origin being stellar mass loss from the luminous stellar figure.

Subject headings: galaxies: internal motions — galaxies: photometry — galaxies: structure — radio sources: galaxies — radio sources: 21 cm radiation

I. INTRODUCTION

As very few elliptical galaxies show detectable quantities of H I, little is known about the origin and distribution of gas in these systems. Studies of neutral and ionized gas in spiral galaxies have revealed the presence of dark matter in extended halos and provided a unique dynamical probe (e.g., oval distortions, warps, etc.). The few ellipticals detected at 21 cm provide unique opportunities for exploring these phenomena in early-type galaxies.

The origin of gas in the few hydrogen rich early-type galaxies remains something of a puzzle, as does the efficient removal mechanism in the rest (cf. Faber and Gallagher 1976). Imaging the distribution of gas in those few ellipticals that are detected in H I is the most promising way to address the issue.

A recent Arecibo survey of low-luminosity ellipticals (Lake and Schommer 1984) produced four galaxies that we were able to map at the VLA, and one other that we were optimistic enough to try without success (NGC 3522). We report here the results of these observations.

The galaxies we imaged have H I emission that extends out to two Holmberg radii. In all cases, this is a strong argument against stellar mass loss. In the discussion section, we point to NGC 7077, an elliptical galaxy caught in the act of capturing a gas-rich companion. UGC 7354 may be another example of this phenomena.

II. OBSERVATIONS AND DATA REDUCTIONS

The radio observations were made with the Very Large Array of the NRAO² in its C configuration (telescope spacings from 0.1 to 3.4 km). Each galaxy was observed for 4 hr, with the exception of NGC 3265 which was observed for 8 hr. Instrumental parameters of the observations are given in Table 1. For each galaxy, we obtained data in a set of 15 narrow-band frequency channels (10 or 20 km s⁻¹) and one broad-band channel (4.8 MHz). Standard VLA calibration procedures were applied to the broad-band channel. To correct for gain variations across the band, each baseline was normalized by the geometric mean of the autocorrelation spectra of the two antennas.

Since the signal was expected to be weak, images were made using natural weighting (Thomson and D'Addario 1981). This optimizes sensitivity at the cost of angular resolution. The final resolution was $\sim 20''$. The broad-band channel map was subtracted from the narrow-band channels to remove continuum sources in the field. Two of the galaxies were detected in the continuum. NGC 5666 has a source of 10 ± 2 mJy, and NGC 3265 has a source of 4 mJy. Both sources are unresolved by a $20''$ beam. The remaining three galaxies were not detected to a level of 2 mJy per beam. The resulting channel maps smoothed to a resolution of $40''$ are shown in Figures 1-4. The contour interval is 2σ , and the velocities are indicated in the upper right corner. The objective of the observations was to get statistical information on the hydrogen distribution in low-

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² The National Radio Astronomical Observatory is operated by Associated Universities Inc., under contract with the National Science Foundation.

TABLE 1
INSTRUMENTAL PARAMETERS

A.

Parameter	Value
Observing date	1983 Apr 23
Shortest spacing	100 m
Longest spacing	3.4 km
FWHI synthesized beam	20" using natural weighting
Number of antennas	27
Number of velocity channels	16
Flux calibrator	3C 286 assuming a flux density of 14.76 Jy at 1414 MHz

B.

Parameter	NGC 3256	NGC 5666	A1230+09	UGC 7354
Channel separation (kHz)	100	100	50	50
RMS in line maps (K)	2.2	3.1	4.1	4.7
Velocity resolution (km s^{-1})	24.8	24.8	12.4	12.4

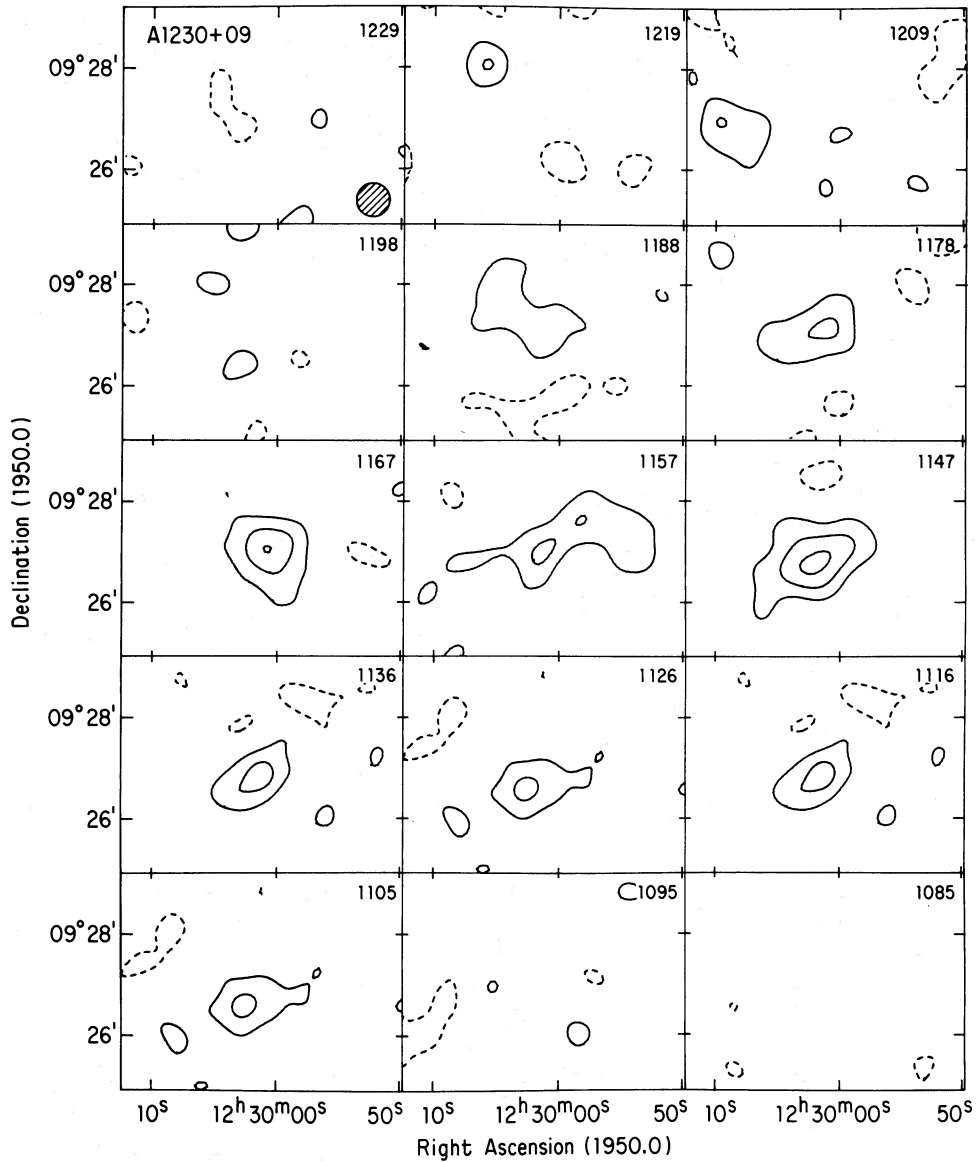


FIG. 1.—Synthesis maps of the 21 cm brightness distribution of A1230+09. The heliocentric radial velocity is shown in the upper right-hand corner of each map. The contour interval is 4 mJy per beam (2σ), negative contours are dashed lines, and the zero contour is suppressed. A peculiar velocity pattern is evident.

H I DISTRIBUTION IN ELLIPTICAL GALAXIES

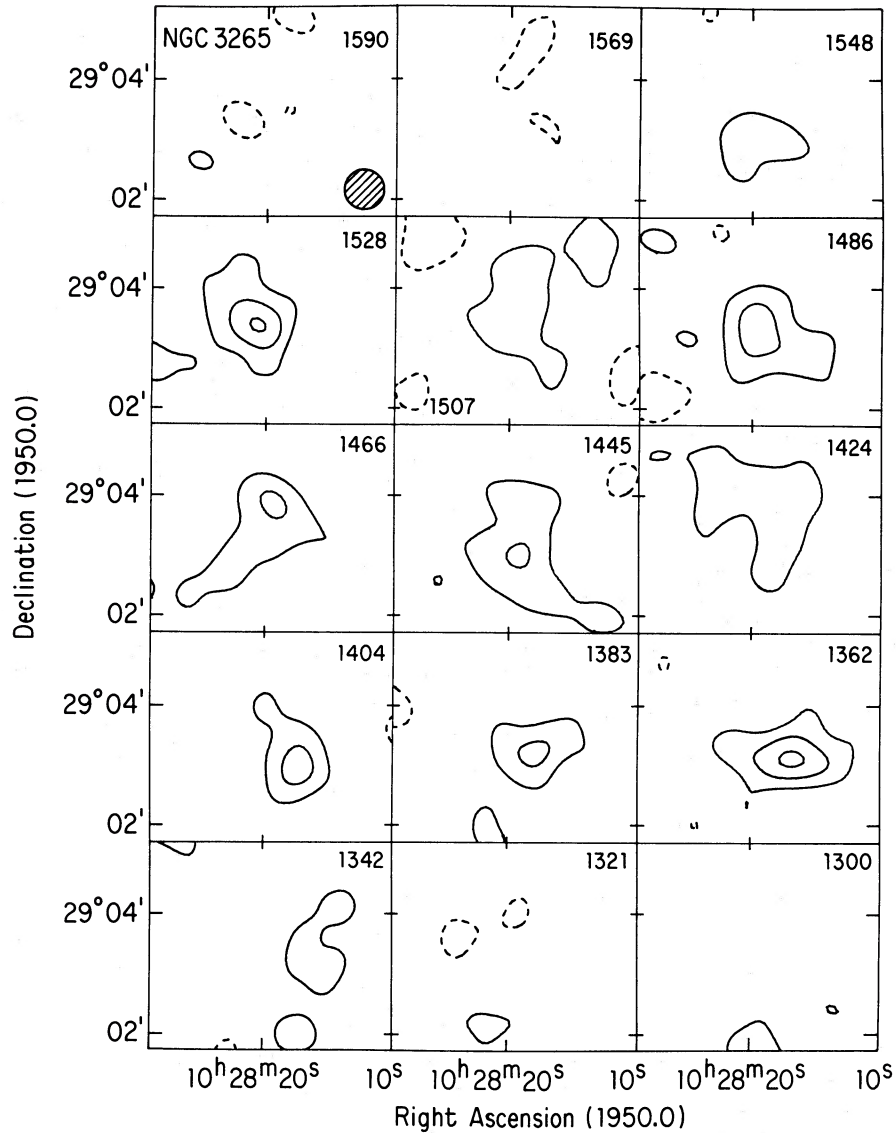


FIG. 2.—Synthesis maps of the 21 cm brightness distribution of NGC 3265. The heliocentric radial velocity is shown in the upper right-hand corner of each map. The contour interval is 2.2 mJy per beam (2σ), negative contours are dashed lines, and the zero contour is suppressed. Systematic rotation is evident. Little wisps seen at the edges should not be considered significant.

luminosity ellipticals rather than detailed information on one galaxy. As a consequence we spent barely enough observing time on each of the galaxies. Nevertheless, it was possible to extract reliable information on the total hydrogen distribution and velocity field from the noisy data. We created masks by introducing 1σ cutoffs to maps made by smoothing the data both spatially and in frequency. We filtered the original data with these masks to enhance weak features that were continuous in either frequency or spatial extent. We can compare the line profiles at the VLA to those of our single dish observations at Arecibo (Lake and Schommer 1984). The FWHM are in good agreement for all the galaxies. The flux agrees to within 20% for NGC 5666 and UGC 7354. The flux measured at the VLA is roughly twice that of the observed Arecibo flux for the other two galaxies. The low signal-to-noise ratio makes the VLA fluxes uncertain in these cases. The total H I maps and position velocity profiles have an angular resolution of $20''$.

The channel maps and velocity fields have an angular resolution of $40''$.

Optical images were obtained to determine the luminosity profiles. NGC 3265 was observed by J. A. Tyson. Five-minute CCD exposures in *B* and *V* of all the other galaxies were taken by the “observe-it-for-us” program at KPNO.

III. DESCRIPTION OF INDIVIDUAL OBJECTS

a) A1230+09

This small elliptical ($D_{25} = 22''$; E1 [RC2]) shows a centrally concentrated, highly elongated H I distribution (Fig. 5). The central H I contours are roughly circular, elongated slightly N-S out to $\sim 20''$ (due to the unresolved beam); the outer regions are very flattened ($2' \times 1'$ at column density 2.2×10^{20} atoms cm^{-2}), with a major axis position angle of about 135° . The optical isophotes have an axis ratio of ~ 1.25 and position

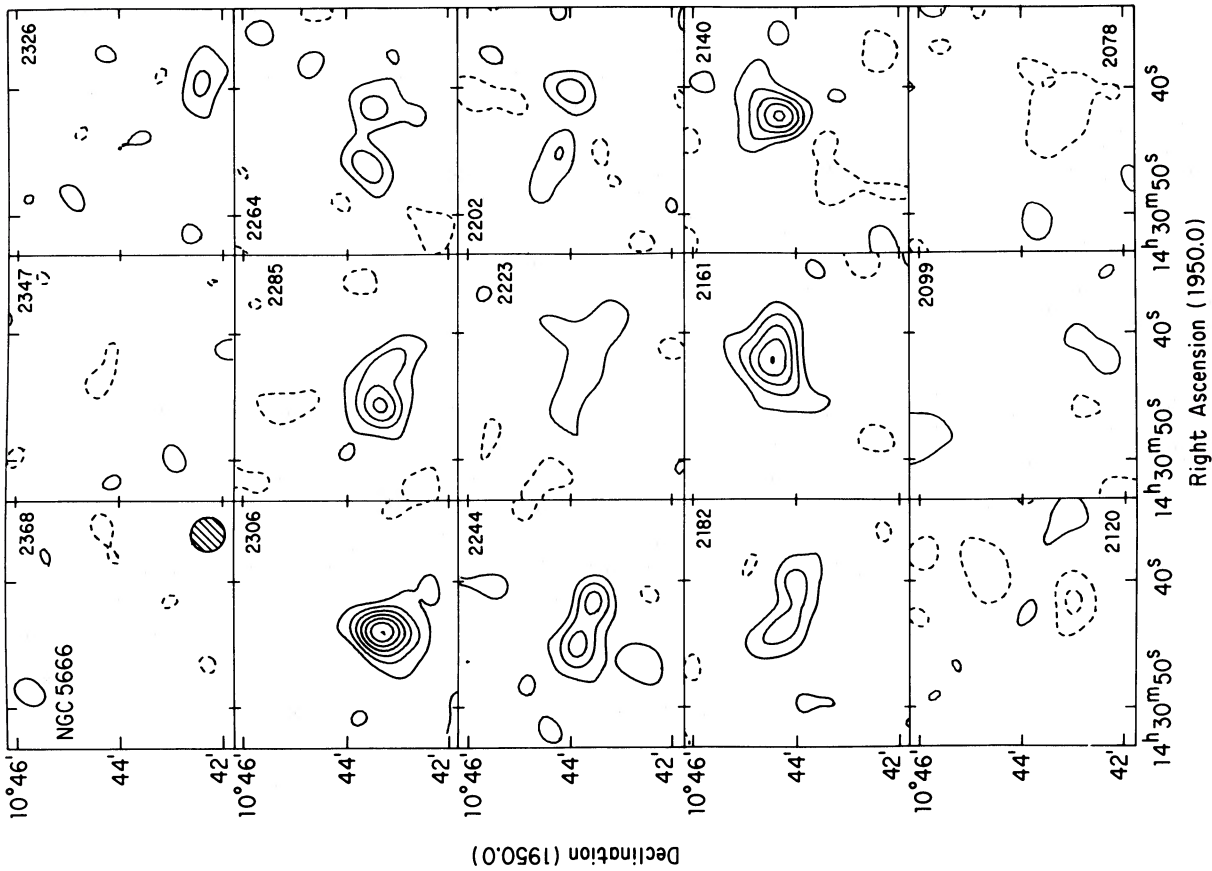


FIG. 3

FIG. 3.—Synthesis maps for NGC 5666. The heliocentric radial velocity is shown in the upper right-hand corner. The contour interval is 2.6 mJy per beam (2σ), dashed lines are negative contours, and the zero contour is not shown. The gross features of the rotation are evident.

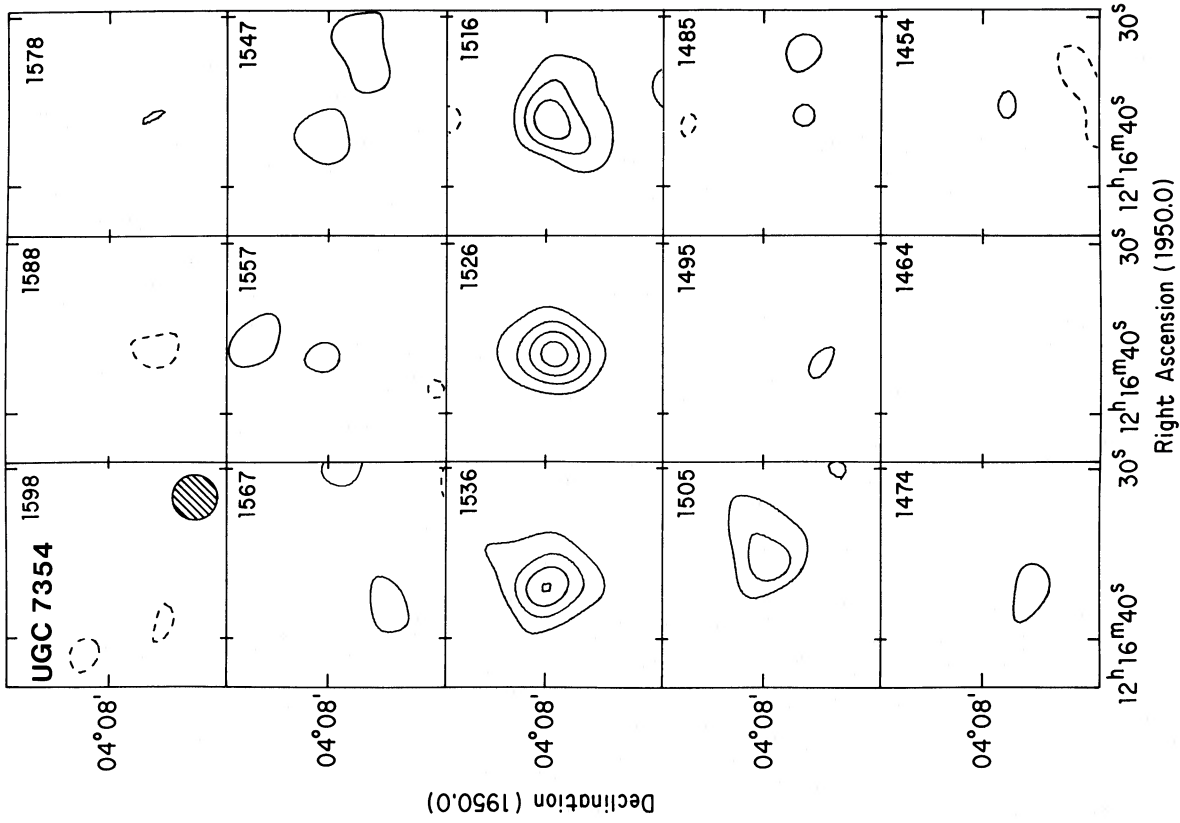


FIG. 4

FIG. 4.—Synthesis maps for UGC 7354. The heliocentric radial velocity is shown in the upper right-hand corner. The contour interval is 5 mJy per beam (2σ), dashed lines are negative contours, and the zero contour is suppressed. It is clear that rotation is not very important.

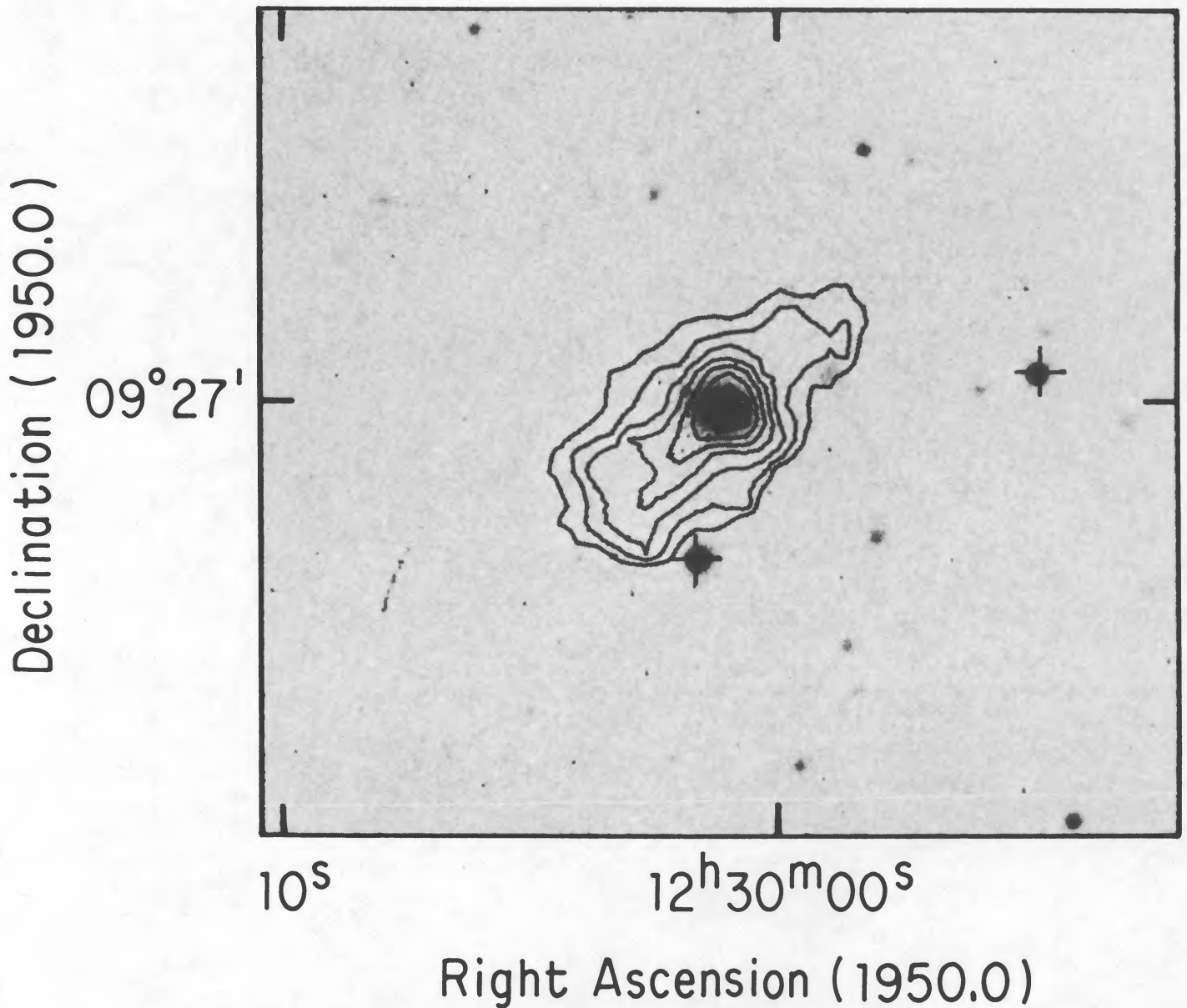


FIG. 5.—The H I contours of A1230+09 superposed on the V CCD frame. Compared to the light distribution, the H I has a radial extent 2 or 3 times greater and is considerably flattened and skewed. The contour interval is 1.5×10^{20} atoms cm^{-2} .

angle of 75° . Compared to the distribution of light, the H I has a radial extent 2 or 3 times greater and is considerably more flattened and skewed.

An unfluxed, nuclear ($1'' \times 2''$ aperture) optical spectrum (Fig. 6), taken at the MMT and kindly provided by G. Bothun, shows obvious [O III] + H β emission lines, but also some dominant red stellar continuum characteristics of early-type galaxies (e.g., strong G band absorption). The optical spectrum resembles an H II region superposed on an elliptical galaxy, leading us to suspect that recent star formation is associated with the central H I. This is consistent with the blue color, $B - V = 0.54$, that we find from our photometry.

The velocity field (Fig. 7) shows apparent rotation of some 30 km s^{-1} peak to peak, along the major axis of the H I distribution. The overall velocity field is not just a disk in circular rotation: the kinematical major axis is at $\text{PA} \approx 160^\circ$,

tilted some 25° – 30° to the H I elongation. “Tilted rotation” does not provide a complete description, as the velocities are clearly distorted in the SE and NW. These distortions are just above the noise. If real, they might be caused by infall or gas motions occurring in both polar and equatorial planes. In either of these cases the gas is not in a stable configuration. See the discussion in § IV.

b) NGC 3265 (UGC 5705)

The H I distribution (Fig. 8a) for NGC 3265 is roughly circular, with a diameter of $2'$ at a column density of 2.2×10^{20} atoms cm^{-2} , but with “blobs” or “spokes” at four position angles ($\sim 10^\circ$, 120° , 190° , and 260°). The optical diameters are 0.9×0.7 (Nilson 1973), with a major axis position angle of 73° . The H I extends a factor of 2–3 beyond the optical radius. The inner H I distribution looks like a “broken” ring, with radius

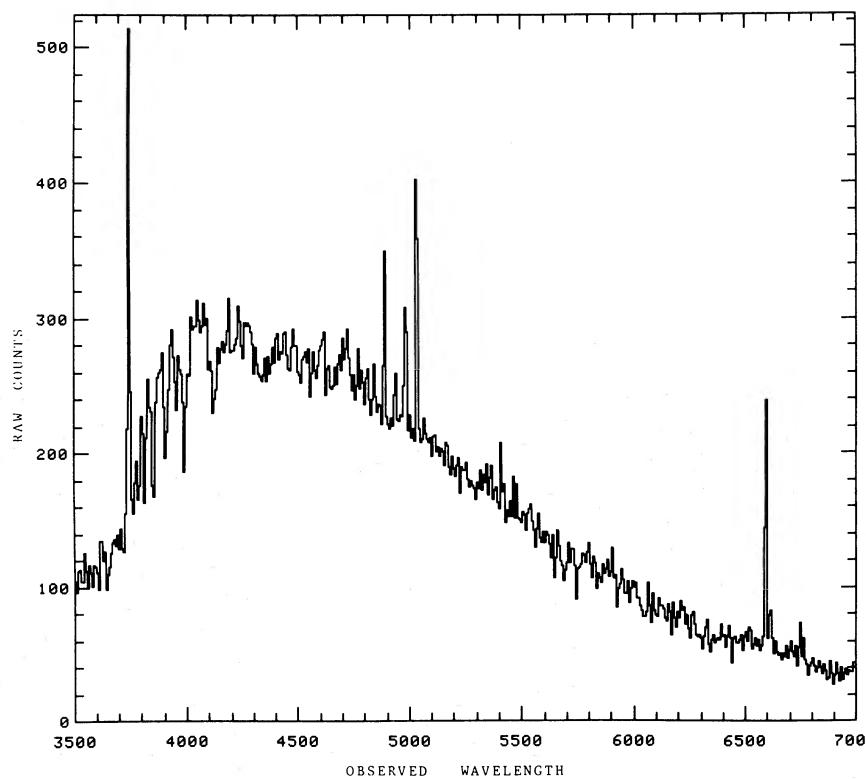


FIG. 6.—An unfluxed, nuclear ($1'' \times 2''$) optical spectrum of A1230+09 taken at the MMT shows [O III] and $H\beta$ emission lines together with the dominant red stellar continuum characteristics of early-type galaxies (e.g., strong G band absorption). (Figure courtesy G. Bothun.)

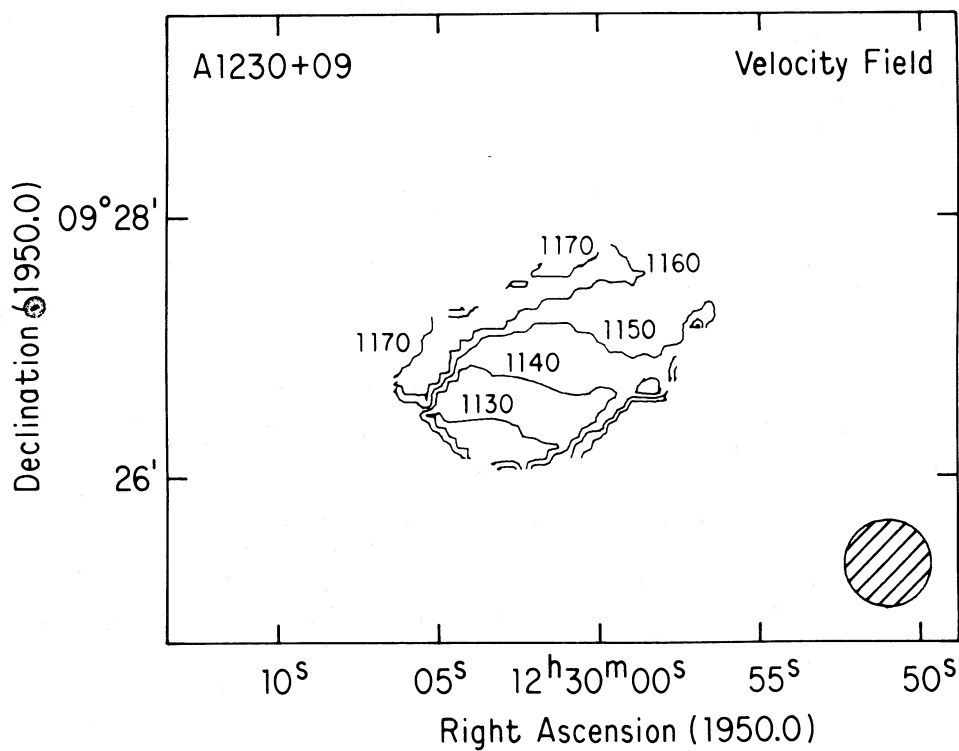


FIG. 7.—The velocity field of A1230+09. Note the apparent rotation of $\sim 30 \text{ km s}^{-1}$ peak-to-peak. It is tilted 25° – 30° relative to the $H\text{ I}$ elongation.

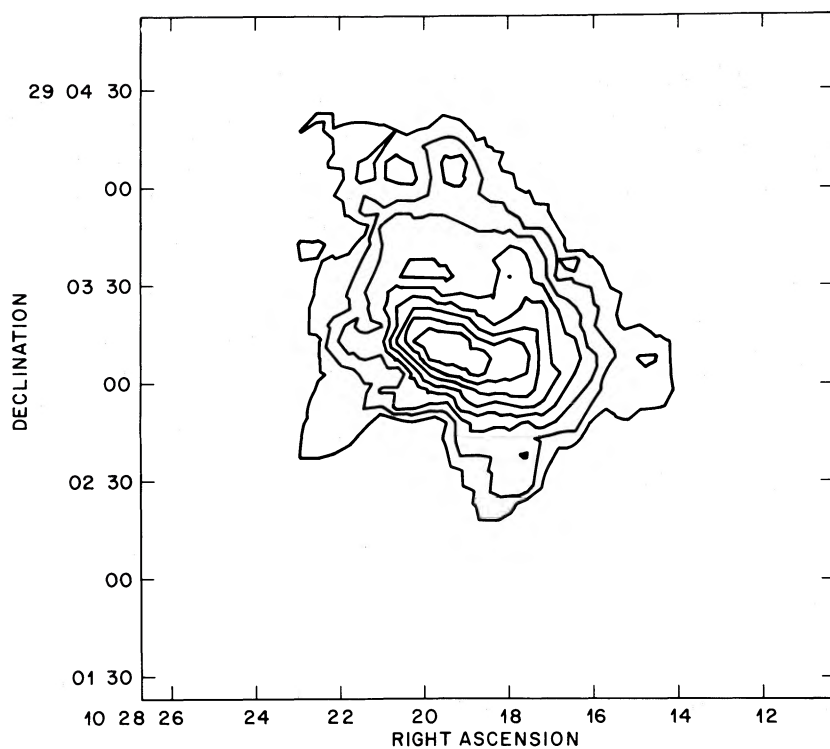


FIG. 8a

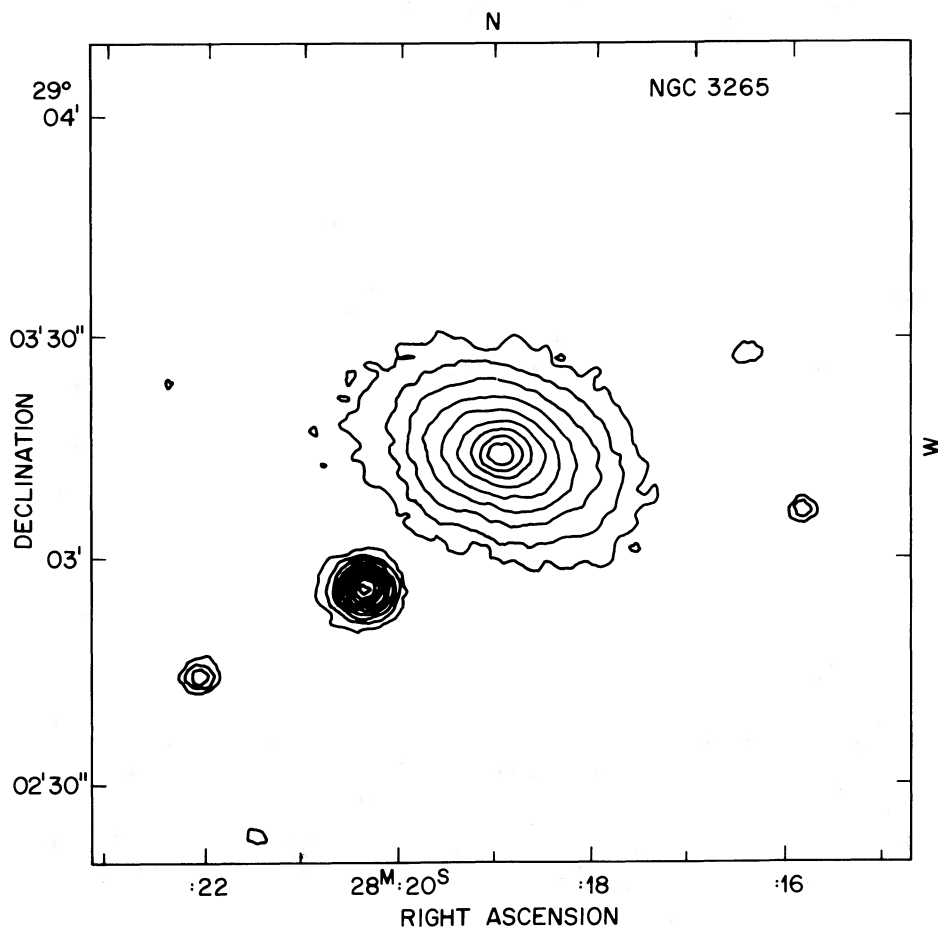


FIG. 8b

FIG. 8.—(a) H I contours of NGC 3265. The inner distribution appears to be a broken ring with a piece on the N-NE side “pulled out” or possibly falling in. The contour interval is 1.5×10^{20} atoms cm^{-2} . (b) Isophotes from a 200 s unfiltered CCD exposure of NGC 3265. Contours are 0.5 mag, the lowest contour is 26 mag arcsec^{-2} . They are elongated at $\text{PA} = 90^\circ$ in the central regions but twist to $\text{PA} \sim 70^\circ$ in the outer region. The optical extent is roughly half that of the H I. (Figure courtesy J. A. Tyson.)

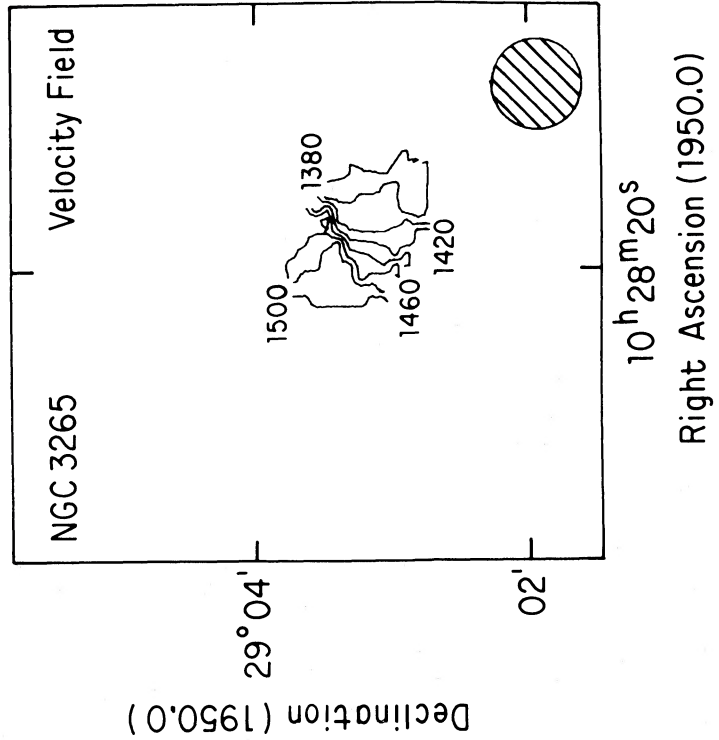


FIG. 9

FIG. 9.—The velocity field of NGC 3265. Maximal rotation of $75\text{--}80\text{ km s}^{-1}$ occurs at a position angle $\sim 75^\circ$. There are clearly noncircular velocities on the NE and SW sides.
 FIG. 10.—A position-velocity plot for NGC 3265 taken along a position angle of 75° . It rises steeply inside the unresolved beam and goes flat on the SW side, but the H I disappears too soon on the NE side to provide a reliable mass estimate.

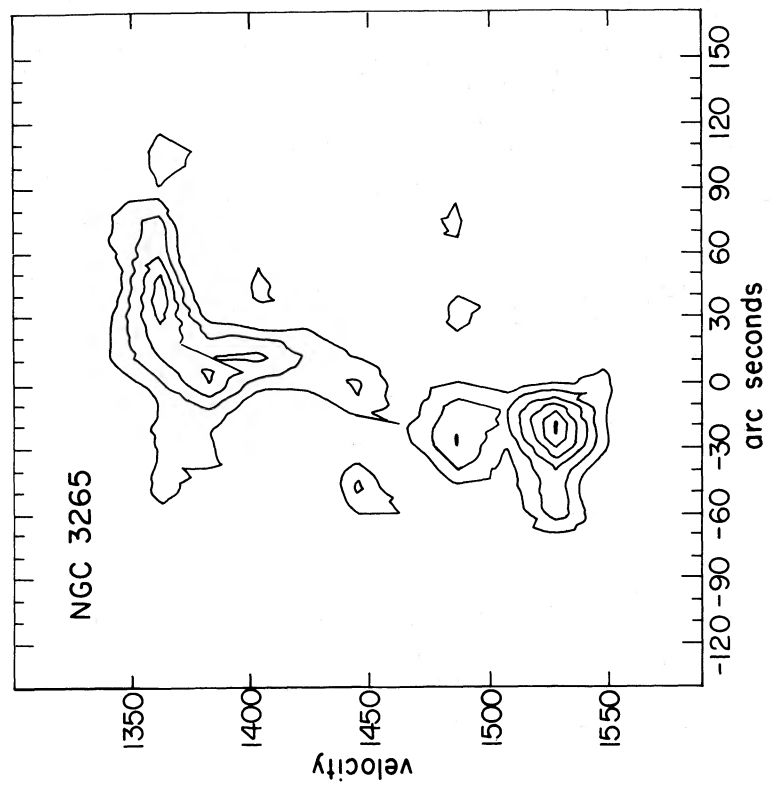


FIG. 10

$\sim 20''$ and a $\sim 30^\circ$ sector on the N–NE side “pulled out” (or possibly “falling in”). In either case, the ring is incomplete.

Figure 8b shows isophotes from a 200 s unfiltered RCA CCD exposure of NGC 3265, kindly provided by J. A. Tyson. The isophotes are elongated at $PA = 90^\circ$ in the central regions, but twist around to a $PA \approx 70^\circ$ in the outermost regions. The luminosity distribution is well fitted by an $r^{1/4}$ function (de Vaucouleurs 1984), consistent with the elliptical classification.

The H I velocity field (Fig. 9) displays maximal rotation at a position angle $\approx 75^\circ$, with $\Delta V = \pm 75\text{--}80 \text{ km s}^{-1}$. There are clearly noncircular velocities or warping present on the NE and SW sides. The rotation curve shown in a position velocity plot taken along the major axis at a position angle of 75° (Fig. 10) rises steeply to $r = 20''$ (1.9 kpc) and goes flat on the SW side, but the H I disappears on the NE side. The non-circular velocity in the NE is associated with the “spoke” there, and is close to the systemic velocity ($\sim 1450 \text{ km s}^{-1}$). The SW spoke has a velocity lower than systemic ($\sim 50\text{--}100 \text{ km s}^{-1}$ less). The isovelocity contours in the inner regions are perpendicular to the gas distribution, as expected from circular rotation, but beyond $r \approx 30''$ the motions are every which way (“infall, outflow, noflow”). The excess gas near the central velocity (Lake and Schommer 1984) seen in the single dish integrated H I profile is mainly the material in the N–NE region. The origin of this gas is unclear. It could be infall or the result of a disruptive tide.

c) NGC 5666

This galaxy is the brightest of the four we observed, having an absolute magnitude $M_B = -18.6$. Morphological information comes from de Vaucouleurs and Pence (1979), who classify it as a compact elliptical ($T = -6$). The luminosity is well fitted by the $r^{1/4}$ function and the $B - V$ color of 0.9 is typical of elliptical galaxies. The distribution of H I (Fig. 11) is elongated with a major axis diameter of $3'$ and a minor axis diameter of 2.5 at the column density of $2.2 \times 10^{20} \text{ atoms cm}^{-2}$. The position angle of the major axis is about 135° ; the optical diameters are 0.9×0.7 , and we determine the position angle from sky survey prints to be $115 \pm 10^\circ$. The gas is more extended than the light distribution by roughly a factor of 3, but oriented in approximately the same direction. The H I distribution is clumpy, with the overall appearance of a ring with two interior bright spots in the N–S direction.

The velocity field (Fig. 12) is regular, rising steeply to $\pm 75 \text{ km s}^{-1}$ at $r \approx 20''$ (2.7 kpc), typical of a disk in circular rotation, but with a hint of a warp in the outer regions. The rotation curve (Fig. 13) remains flat out to at least $1'$. The kinematical major axis lies at a position angle of $\sim 155^\circ$, in poor agreement with the gas distribution.

We now turn to our optical data. We adopt the simple model for the distribution of light in ellipticals proposed by Jaffe (1983). It has a spatial distribution of light

$$E(r) = \frac{L_{\text{tot}}}{4\pi r^2(1+r)^2},$$

where r is normalized to the radius containing half the total light in space. Analysis of our photometry sets this radius at $4.6''$.

NGC 5666 provides a unique opportunity to study the distribution of dark matter in an elliptical galaxy. The velocity field is regular and the gas extends to nearly 20 times the half-light radius. The previous record holder for disk radius to

half-light radius is NGC 3198 (van Albada *et al.* 1985), where this ratio is slightly greater than 4. A first analysis shows that the M/L increases by a factor of 4 from the central regions to the outermost point detected. Unfortunately our low-resolution data does not meet the Sancisi rule that one must have five beams to look at changes in the mass-to-light ratio. We are planning further observations in the C and D arrays to capitalize on this unique opportunity.

d) UGC 7354

The H I distribution (Fig. 14) of UGC 7354 shows the gas to be centrally concentrated, and roughly circular in the outer parts, with a diameter of ~ 1.5 at column density $2.2 \times 10^{20} \text{ atoms cm}^{-2}$. The optical diameters are 0.5×0.4 (Nilson 1973); the gas again extends out to 2–3 times the optical radius. The inner H I is elongated along a position angle of $\sim 50^\circ$, and the H I peak intensity is displaced to the NE about $15''$ from the centroid determined by the outermost contours. Thus, the outer gas is distended to the SW.

The velocity field (Fig. 15) is not well ordered; there is a hint of rotation in the plane at a position angle of 60° , with peak to peak amplitude of 20 km s^{-1} .

The appearance of UGC 7354 on the Sky Survey is asymmetric and rather confusing (see Sandage and Binggeli 1984). Careful inspection of our CCD frame shows two components: a bright compact elliptical galaxy; and a diffuse, disklike object, without a prominent nucleus, located about $10''$ to the SE. Presumably the compact E is the source of the optical emission lines which give this object its designation as Haro 8. The H I is elongated at the position angle of the diffuse disk, which is likely its source. The galaxies must be an interacting system; the optical and H I emission-line velocities agree to within 50 km s^{-1} .

IV. DISCUSSION

The velocity field of NGC 5666 is regular enough to provide a probe of the mass distribution of the galaxy. With our limited resolution, we can only point to this galaxy as an excellent candidate for further study. The ratio of gas extent to half-light radius is 4–5 times greater than observed in the record-holding spiral galaxy NGC 3198 (van Albada *et al.* 1985). We are following up on this object, obtaining more data in the C and D configurations.

For several more luminous ellipticals, M/L ratios have been determined using H I rotation curves, e.g., NGC 4278 (Raimond *et al.* 1981), NGC 1052 (van Gorkom *et al.* 1986), and NGC 5128 (van Gorkom 1986). However, for these galaxies, which have a less regular H I distribution, only averages M/L ratios have been determined.

In previous papers (Lake 1983; Lake and Schommer 1984), we have emphasized the dependence on luminosity of the rotation properties and gas content of elliptical galaxies. We caution that halo properties may also vary with luminosity.

It is now well established in the more luminous ellipticals that the gas has an external origin, and is not produced by mass loss (Knapp 1986; van Gorkom *et al.* 1986). Our results for the H I extent in the low-luminosity objects suggest that even in these galaxies the gas origin is likely external. Stellar mass loss is not the source of cool gas in any of these elliptical galaxies. An attractive alternative is that some ellipticals have eaten gas-rich companions (e.g., Silk and Norman 1979). This conclusion is an uneasy one, since ellipticals seem to have very few dwarf companions (Bothun and Sullivan 1977).

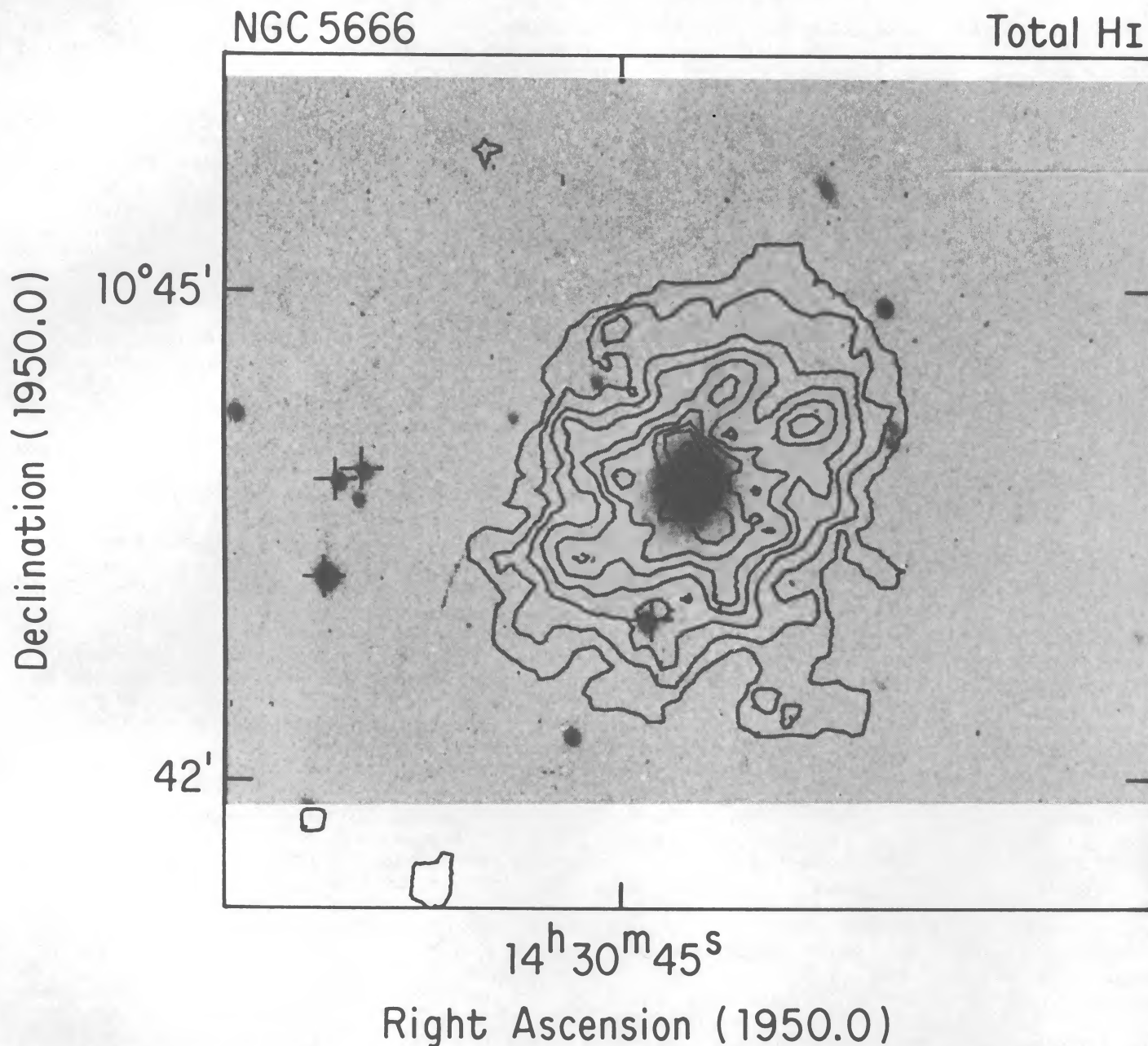


FIG. 11.—H I contours of NGC 5666 overlaid on the V CCD frame. The gas is more extended than the light by roughly a factor of 3, but oriented in the same direction. The H I distribution is clumpy, with an overall appearance of a ring with two interior bright spots. The contour interval is 1.5×10^{20} atoms cm^{-2} .

It would be unfortunate to have this scenario enter the folklore of the field without a single example of an elliptical in the act of eating a companion. Fortunately NGC 7077 and UGC 7354 provide just such examples. We intended to observe NGC 7077 as part of our program of H I observations of low-luminosity ellipticals. Before we did so, it was detected in H I at Arcicibo by B. M. Lewis (private communication) and observed optically by G. Bothun. Bothun's CCD frame shows a small blue (presumably gas-rich) companion inside the optical body of the galaxy. NGC 7077 had been caught in the act of capturing a companion.

In reviewing the data on H I in ellipticals, we find two morphological features of the gas that argue strongly for the existence of hot winds. In NGC 3265 and NGC 5666, we find the usual pattern for bright ellipticals, the gas lies in a gapped disk.

The size of the gap is comparable to the half-light radius of the galaxy. Winds seem a plausible explanation for this.

The second feature is the pronounced irregularities. The longest rotation period for any of the gas we have observed is about two percent of a Hubble time. Yet, only NGC 5666 is a disk in equilibrium. What has happened to all the elliptical galaxies which captured companions over a billion years ago?

The answer to this question quickly leads into the thorny issues of morphology. There is growing evidence for a class of compact, high surface brightness ellipticals (cE's) that would include NGC 5666, A1230, and probably "component A" of UGC 7354 (see Kormendy 1985; Wirth and Gallagher 1984). These objects are distinct from the "amorphous" class designated by Sandage and Brucato (1979) in that they show no sign of the filamentary optical structures seen in NGC 3077 and M82

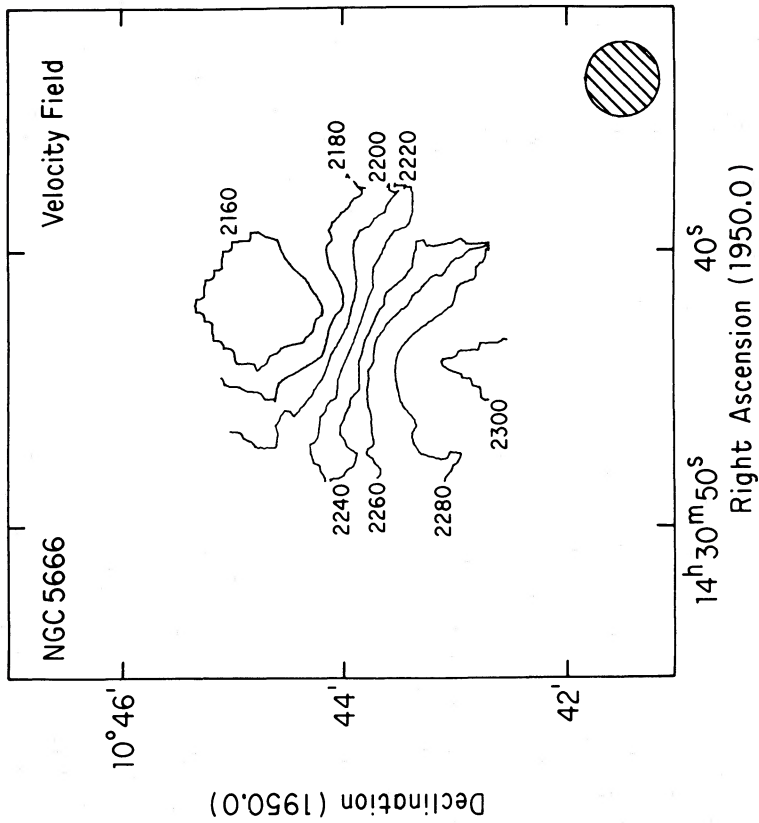


FIG. 12

FIG. 12.—The velocity field of NGC 5666 is regular

FIG. 13.—The position-velocity plot for NGC 5666 taken at PA = 155°. It rises steeply to $\pm 75 \text{ km s}^{-1}$ inside the unresolved beam which is $\sim 20''$ (2 kpc for a distance of 27.6 Mpc). The rotation curve is flat out to at least 1'.

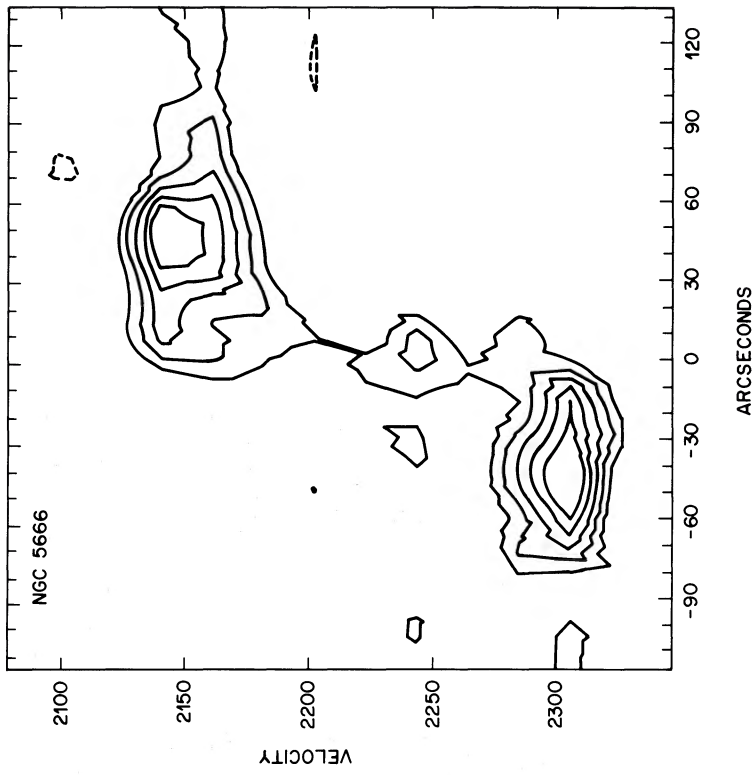


FIG. 13

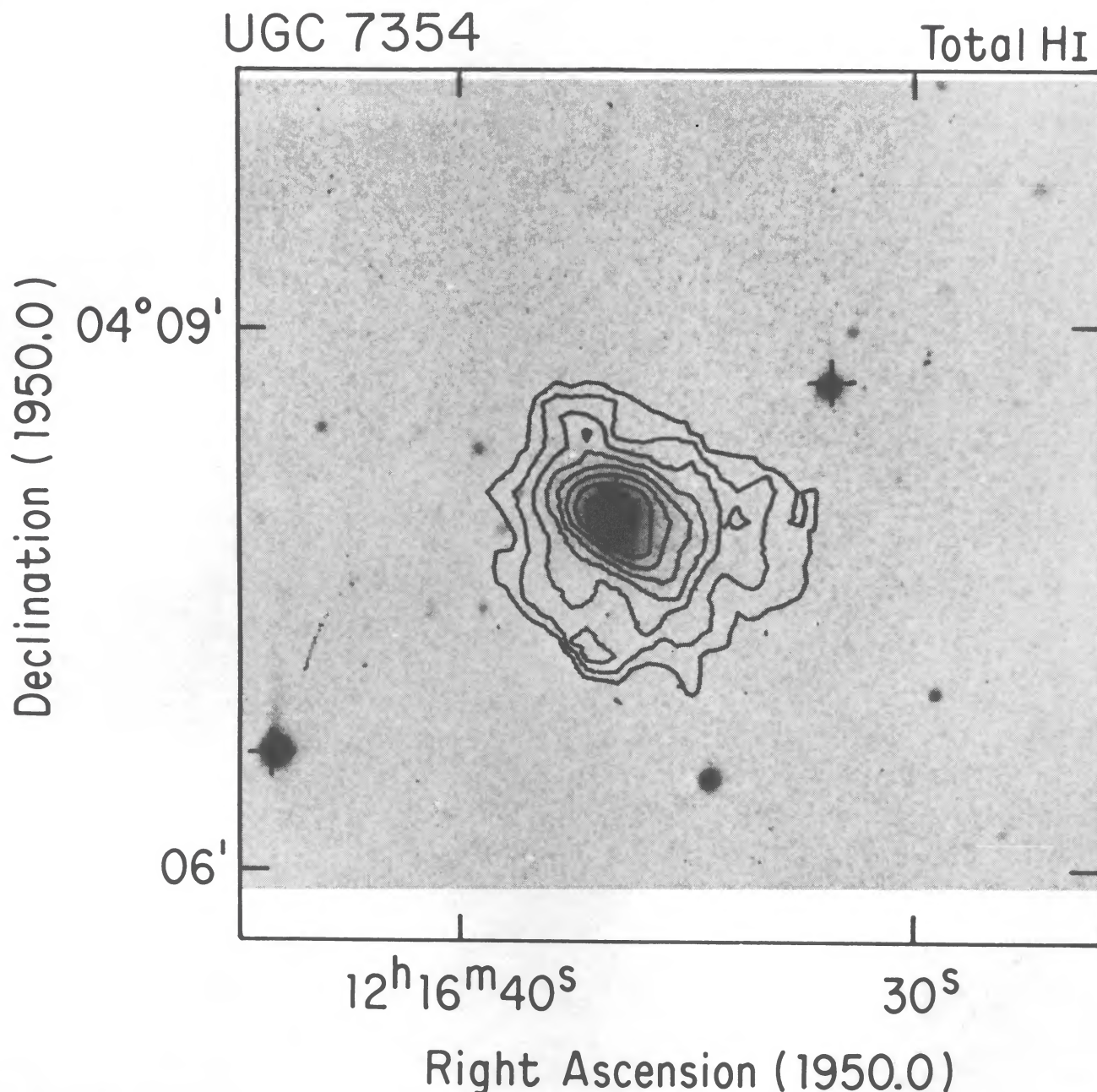


FIG. 14.—The H I contours of UGC 7354 overlaid on a *B* CCD frame. The gas is centrally concentrated and nearly circular in the outer parts but again extends to 2–3 times the optical radius. The contour interval is 1.5×10^{20} atoms cm^{-2} .

(the prototypical amorphous galaxies). The cE's may be distinct from BCDs (Sandage and Bingelli 1984), but it is hard to separate objects based only on morphology. A1230 is a good example of this difficulty. Humason, Mayall, and Sandage (1956) classify it as an elliptical (E1, with G2 optical spectrum) while Sandage and Bingelli (1984) classify it as a BCD. Gottesman and Weliachew (1977) suggest that Ir 0 and Ir II's were S0's and Es before the capture of a companion. The sample of elliptical and lenticulars with dust lanes is growing rapidly. This is evidence that many galaxies may have accreted companions long ago. Until there is a larger sample, no conclusion is possible. Our experience does leave us with a feeling that the H I is likely to be blown out of the galaxy or evaporated before it has an opportunity to settle into an equilibrium configuration.

Why are there more low-luminosity ellipticals with gas? The

scenario of mass loss and cooling proposed by us in a previous paper is clearly wrong. We present a germ of a new idea. The galaxy-galaxy correlation function is known to be nearly independent of luminosity (*cf.* Lake and Tremaine 1980). This fact leads us to presume that the capture rate of gas-rich dwarfs by ellipticals could well be independent of luminosity. Can the gas survive for a longer time inside the low-luminosity ellipticals?

When a gas-rich companion is tidally disrupted, the gas outside the optical radius will be slowly evaporated by the gas observed in X-rays around luminous early-type galaxies, (Forman, Jones, and Tucker 1985). To date X-ray emission has not been detected in low-luminosity ellipticals, nor is it likely to be.

Hot halos of gas are only maintained when the heating rate exceeds that of cooling. The rate of cooling has a strong feature at a temperature of a couple million degrees, which is the virial

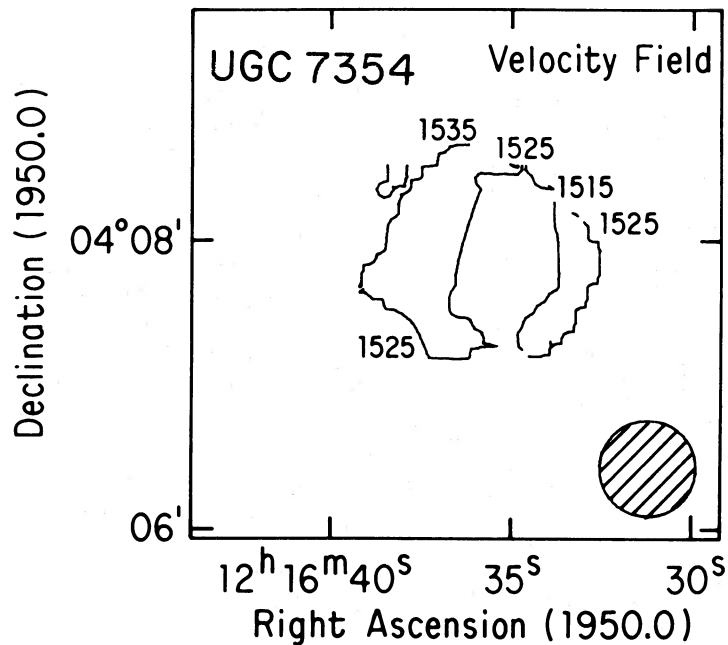


FIG. 15.—The velocity field of UGC 7354 is chaotic. Some rotation (peak-to-peak amplitude of 40 km s^{-1}) at a position angle of 60° is evident.

temperature of gas in a galaxy with a luminosity of roughly $10^9 L_\odot$ (see Lake and Schommer 1984). In galaxies less luminous than this, cooling prevails, and the extensive hot gas necessary to evaporate the tidal debris of a captured dwarf is not there.

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