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H I OBSERVATIONS OF THREE *IRAS* DETECTED ELLIPTICAL GALAXIES

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ABSTRACT

Three elliptical galaxies with strong far-infrared emission (*IRAS* flux density greater than 1 Jy at 100 μm) were observed in the H I 21 cm line with the VLA. Only one of these, the dwarf NGC 855, was detected. This galaxy has an extended H I distribution which is highly inclined to the optical major axis and a weak radio continuum source. Deep optical images show complex structure in the inner regions and emission lines suggestive of star formation. It is likely that this star formation and the cool interstellar medium (ISM) are sources for the far-IR luminosity. IC 1459 is in a group containing several spirals and shows signs of recent interaction. Neutral hydrogen was not detected, but there is a powerful central radio continuum source, and the 100 μm emission is plausibly explained as arising from this source. NGC 6958 has only weak radio continuum emission, and the lower limit on $L_{\rm IR}/M_{\rm H\,I}$ is at the high end of the range for this quantity among ellipticals. It is likely that a small amount of dust heated by a strong radiation field is providing the far-infrared luminosity.

The infrared properties of these galaxies are similar, but the IR emission seems to have three different origins, complicating the interpretation of *IRAS* data for ellipticals.

Subject headings: galaxies: interactions — infrared: sources — radio sources: galaxies — radio sources: 21 cm radiation

I. INTRODUCTION

The *Infrared Astronomical Satellite* has provided copious data on the IR properties of astronomical objects, with close to all-sky coverage. Knapp *et al.* (1989) extracted the information pertinent to elliptical and S0 galaxies from this data base. Almost 50% of the E's were detected with $S_{60\,\mu\rm m}/S_{100\,\mu\rm m}$ typically $\frac{1}{3}$, suggesting a cool thermal source. Hence, a common assumption is that the far-infrared emission is due to reradiation of starlight by dust grains and that its presence implies the presence of cold gas (e.g., Jura 1986). Since there are many more ellipticals detected at 100 μm than in the 21 cm line of neutral hydrogen, it is tempting to use the *IRAS* data as indicators of the mass of cool interstellar matter in early-type galaxies.

However, there is little direct evidence that dust is responsible for the IR radiation. (The dust referred to here need not be detectable as dust lanes or patches seen in absorption, because the optical depth is not required to be high to account for the IR/blue luminosity ratio. A preferred orientation would be necessary to reveal the dust optically.) In general, it is not known if the infrared emission has a "predictable" source in the sense of whether galaxies with similar IR properties (specifically colors) may be assumed to be manufacturing this luminosity in a like manner.

Only a minority of elliptical galaxies possess enough H I to have been detected in the 21 cm line even in sensitive observations—about 15%, according to the extensive tabulation of Knapp, Turner, and Cunniffe (1985). The mass of neutral hydrogen in those detected is typically in the range 10^6–$10^9\ M_\odot$, well below that associated with later type galaxies. While all of this suggests few ellipticals contain much H I, there are other indications that most (if not all) do have a cool ISM component. Sadler and Gerhard (1985) estimate that dust lanes or patches are present in roughly 45% of E's (see also Ebneter, Djorgovski, and Davis 1987). Knapp *et al.* (1989) find that a similar fraction has been detected by *IRAS* at 100 μm. Further analysis of the *IRAS* results suggest the reason for the detection rates not being higher is simply the flux limiting of the more distant galaxies in the sample. When this is taken into account, most E's are shown to be producing far-IR emission of at least 0.1% of the blue luminosity (see, e.g., Marston 1988; Walsh and Knapp 1989).

Synthesis mapping of the H I has now been performed for several ellipticals, including NGC 4278 (Raimond *et al.* 1981), NGC 1052 (van Gorkom *et al.* 1986), NGC 3265 and NGC 5666 (Lake, Schommer, and van Gorkom 1987), and NGC 2974 (Kim *et al.* 1988). (All of these are detected strongly by *IRAS*.) One feature common to these observations is the indication that the neutral hydrogen is largely kinematically independent of the stellar content of the galaxies. For example, the rotation axes of the two components are misaligned in both NGC 1052 and NGC 4278. The H I is also seen to extend out to several Holmberg radii in NGC 1052 and NGC 5666. Such differences between the hydrogen and the rest of the galaxy often lead to the conclusion that the H I is external to the galaxy in its origin (e.g., van Gorkom *et al.* 1986), being gained by infall, by mergers with gas-rich dwarfs, or by tidal interactions with nearby spirals. There is also much difficulty in providing the specific angular momentum for dust in disks or rings if its origin is mass loss from stars. This again suggests the

TABLE 1

INSTRUMENTAL PARAMETERS

A. GENERAL INFORMATION

Observational Parameter	Value
Number of Antennas	27
Primary Beam	30′
Number of Frequency Channels	31
Velocity Resolution	42 km s^{-1}
Flux Calibrator	3C 48

B. GALAXY SPECIFIC ITEMS

Observational Parameter	NGC 855	NGC 6958	IC 1459
Observing Date (1988)	August 17	August 17	August 15
Field Center (1950)	$\alpha = 02^h11^m10^s$	$20^h45^m30^s$	$22^h54^m23^s$
	$\delta = 27°38'36''$	$-38°10'54''$	$-36°43'48''$
Velocity at Band Center (km s^{-1})	600	2627	1691
Synthesized Beam (Channel)	58″.86 × 58″.24	134″.31 × 43″.84	111″.55 × 46″.74
Position Angle	−47°.03	−4°.99	11°.18
Synthesized Beam (Continuum)	...	...	86″.24 × 34″.29
Position Angle	...	...	10°.16
Equivalent T_b for 1 mJy/beam	0.18 K	0.11 K	0.12 K
rms Noise: Channels (mJy/Beam)	0.5	1.0	1.0
Continuum (mJy/Beam)	0.25	0.5	1.0
Phase Calibrator	0221+276	2058−425	2259−375

hydrogen is not intrinsic to the galaxy (once dust is equated with gas). Various statistical arguments point in the same direction, basically concluding that the wide scatter found in the ratio of blue luminosity and some property of the ISM such as mass of H I or 100 μm flux density arises because they are essentially independent, as would be the case if there was an external origin. (See Knapp, Turner, and Cunniffe 1985; Walsh and Knapp 1989.)

In light of the above, we looked for H I in three ellipticals strongly detected by *IRAS* at 100 μm. These galaxies also showed evidence of having experienced mergers (e.g., they apparently contain dust—seen in absorption—and/or shells).

The observations and data reduction procedures are outlined in § II. For each galaxy, we describe the H I results, briefly review previous knowledge, and speculate on possible explanations (§ III for NGC 855, § IV for IC 1459, and § V for NGC 6958). Conclusions are summarized in § VI.

II. DATA REDUCTION

The 21 cm line observations were made in 1988 August with the Very Large Array of the NRAO[1] in its D configuration, using all 27 antennae. Each galaxy was observed for about 4 hours and calibrated against 3C 48, for which a flux density of 15.8 Jy at 1413 MHz was assumed (Baars *et al.* 1977). Table 1 lists the various instrumental parameters used (general information in Table 1A with galaxy specific items in 1B). The central velocities were from Burstein *et al.* (1987) for NGC 855 and NGC 6958 and between the velocity given by Burstein *et al.* and by Franx and Illingworth (1988) for IC 1459. The velocity coverage was wide enough ($\sim$1200 km s^{-1}) to ensure the inclusion of any H I associated with the galaxies. Throughout this paper, velocities are heliocentric and defined as $v = c\Delta\lambda/\lambda_0$. Where absolute quantities are needed, $H_0 = 100$ km s^{-1} Mpc^{-1} has been used with a pure Hubble flow.

Two IFs were used, on-line Hanning smoothing was applied to the data, and a bandpass calibration was applied. Natural weighting was used for the images. The continuum maps were formed by adding together end velocity channels which appeared line free. These were CLEANed to a level of $\sim 1\ \sigma$. The line maps were produced by subtracting the averaged (pre-CLEANed) continuum from each channel and then CLEANing the channels which showed some signal,

In order to produce maps of the total H I distribution and of the velocity field, a second set of the line maps was produced which were Gaussian smoothed to a spatial resolution of 75″ and Hanning smoothed to a velocity resolution of $\sim$80 km s^{-1}. The total H I map and intensity-weighted velocity field were calculated from the unsmoothed line maps, using only those regions where the signal strength was greater than 2 σ in the smoothed line maps.

III. NGC 855

This is a nearby, fairly isolated dwarf which appears considerably flattened with major and minor axes of 3′.3 × 1′.4 according to the ESO catalog (Lauberts 1982).

A summary of previous observations is given in Table 2. The color and magnitude come from Burstein *et al.* (1987) (they are corrected for extinction) and the *IRAS* data are from Knapp *et al.* (1989); the limits are 3 σ. The 6 cm detection is taken from Wrobel and Heeschen (1989), and the 13 cm limit is an Arecibo observation by Dressel and Condon (1978). The possible presence of dust near the nucleus of NGC 855 has also been reported (Ebneter, Djorgovski, and Davis 1988). The $B-V$ color is one of the bluest for any elliptical observed by Burstein *et al.* (1987).

a) *Continuum*

At 20 cm, we detected an unresolved source from NGC 855 with a flux density of 4.5 mJy (Table 3). Wrobel and Heeschen (1989) found an extended source of strength 2.3 mJy at 6 cm

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TABLE 2

Previous Observations of NGC 855

Parameter	Value
Optical	
B_T	13.12
$B-V$	0.68
Infrared	
Flux Density (mJy) at 12 μm	<87
Flux Density (mJy) at 25 μm	<153
Flux Density (mJy) at 60 μm	1410
Flux Density (mJy) at 100 μm	3270
Radio Continuum	
Flux Density (mJy) at 6 cm	2.3 ± 0.3
Flux Density (mJy) at 13 cm	<15

TABLE 3

Continuum Flux Densities

Galaxy	Flux Density (mJy)	R.A.	Decl.
NGC 855	4.5	$2^h11^m11^s$	27°38′36″
NGC 6958	19.1	20 45 30	−38 11 09
IC 1459	1140	22 54 23	−36 43 48

using the VLA in its C configuration. The source size is 14″.6 × 9″.2 at position angle 59°.

A candidate for such a source is star formation. Wunderlich, Klein, and Wielebinski (1987) and others have shown that spiral galaxies display a very tight linear correlation between radio and far-IR luminosities (but see Devereux and Eales 1989). The details are not well understood, but the link is often attributed to star formation, the IR arising from dust grains heated by young stars and the radio emission from supernovae and their remnants. While very few ellipticals show this relationship (Walsh *et al.* 1989), having more powerful central radio sources, NGC 855 could be an exception, an elliptical galaxy producing stars. (Walsh *et al.* report NGC 855 as a nondetection at 6 cm; the data have since been rereduced, searching for extended emission, and the source described above has been found.) The ratio of the 20 cm continuum flux to far-infrared flux is only about 1 σ away from the typical spiral galaxy ratio as given by Unger *et al.* (1989), having a slightly low radio power per unit of far-IR emission; likewise for the 6 cm power. The 21 cm and 6 cm flux densities show that the NGC 855 spectral index is similar to that of star-forming systems. Wrobel and Heeschen (1988) found extended radio sources in other ellipticals which may also be due to star formation.

CCD images and spectra of this galaxy show the existence of three possible H II complexes toward the center of NGC 855, lending support to the star formation hypothesis. These data are discussed elsewhere (Wallington *et al.* 1989). Sadler (1987; see also Sadler, Jenkins, and Kotanyi 1989) has argued that low-luminosity ellipticals tend to have emission-line properties similar to H II regions; it seems that NGC 855 is representative of this class.

b) *Neutral Hydrogen*

Figure 1 shows the total H I map of NGC 855. The distribution is far more extended than the area occupied by the star-forming regions, indicated by the extent of the 6 cm continuum emission. The velocity gradient suggests that much of the hydrogen is on orbits highly inclined to the major axis; again, this is more fully discussed by Wallington *et al.*

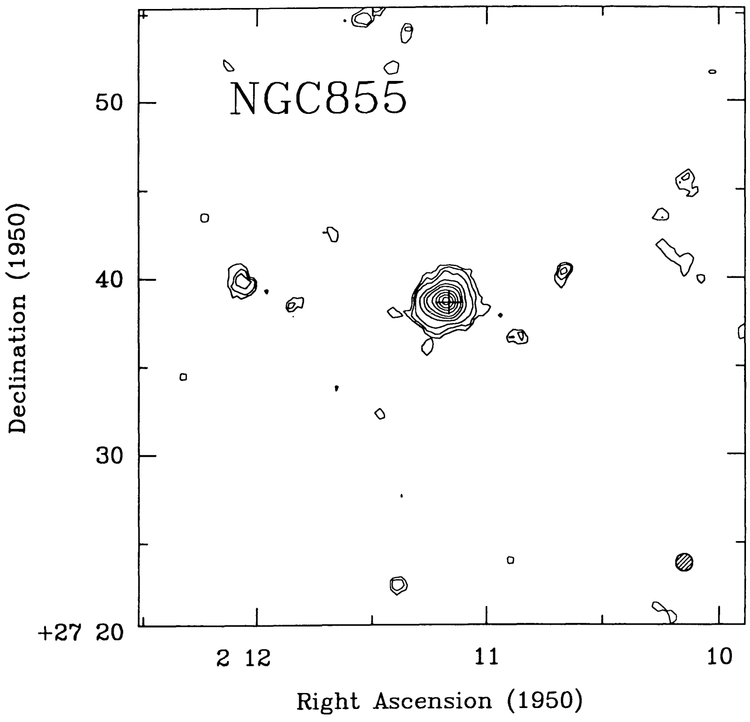

Fig. 1.—Total H I map of NGC 855. Cross marks the position of the galaxy from the ESO catalog. The contours denote column densities of 1.5, 3, 5, 10, 15, 20, 30, 40, 50, and 60 × 10^{19} atoms cm^{-2}. The beam is shown in the lower right.

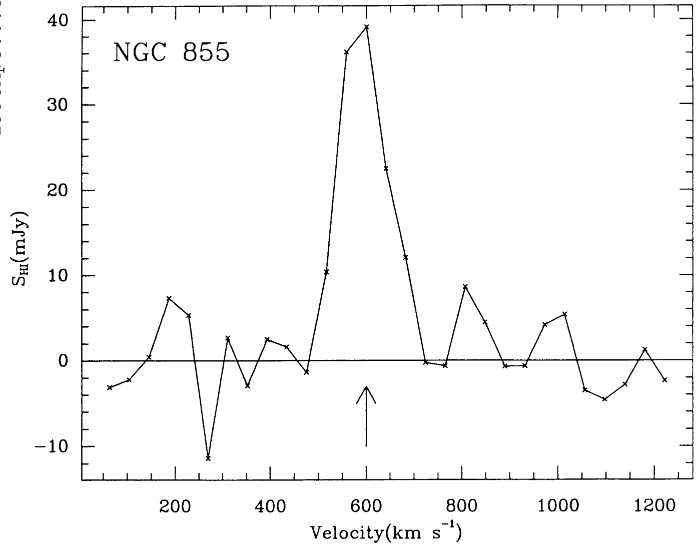

FIG. 2.—H I line profile for NGC 855; arrow indicates the systemic velocity

Since the H I is detected in a region only a few times larger than the beam, it is difficult to determine its inclination accurately from assuming that it lies in a circular disk or ring. If the gas is on circular orbits, a lower limit to the mass-to-light ratio can be obtained by assuming it to be edge-on. (A factor of 2 smaller mass estimate would result from assuming radial infall, which could be possible if the gas were recently acquired. However, the choice of circular orbits is supported by the velocity data, which show clear evidence for rotation.) The mass in solar units within radius r kpc is given by $M_r = 2.33 \times 10^5\, rV_c^2$. The circular velocity, V_c and apparent velocity, V, are related by $V_c \sin i = V$, i being the inclination angle. The distance is taken as 6 Mpc and the velocity is taken as 80 km s^{-1} (the half-width at 25% of the peak flux density in Fig. 3) at 1′ from the center. Since most of the blue light is within this aperture, the total blue magnitude, B_T, is used to calculate luminosity. The result is $M/L \sim 8/\sin^2 i$ in solar units. (The uncertainties in this value are large, however, particularly because the poor spatial resolution prevents accurate estimation of the extent of the neutral hydrogen.)

The line profile for the galaxy is given in Figure 2, and the central velocity agrees well with the optical value. The total flux density (Table 4) was obtained simply by summing the area under the profile; i.e., no fitting or smoothing of the data was performed. This H I mass is comparable with that in other elliptical galaxies in which H I has been detected but is far smaller than for spirals. Yet NGC 855 appears to be forming stars in a manner similar to the late-type galaxies, albeit on a much reduced scale. In spiral galaxies, the ratio of neutral hydrogen mass to far-infrared luminosity varies considerably (Fig. 3), and it is not clear whether the dust responsible for the far-IR emission is immediately associated with star formation (e.g., Young 1987) or with the more diffuse ISM (e.g., Persson and Helou 1987); in NGC 855, the former is more likely.

TABLE 4

H I CONTENT OF THE ELLIPTICAL GALAXIES

Galaxy	H I Flux (Jy km s^{-1})	Distance (Mpc)	Mass ($M_\odot$)
NGC 855	4.9	6.0	4.1×10^7
NGC 6958	<2.2	26.3	$<3.7 \times 10^8$
IC 1459	<3.0	16.9	$<2.0 \times 10^8$

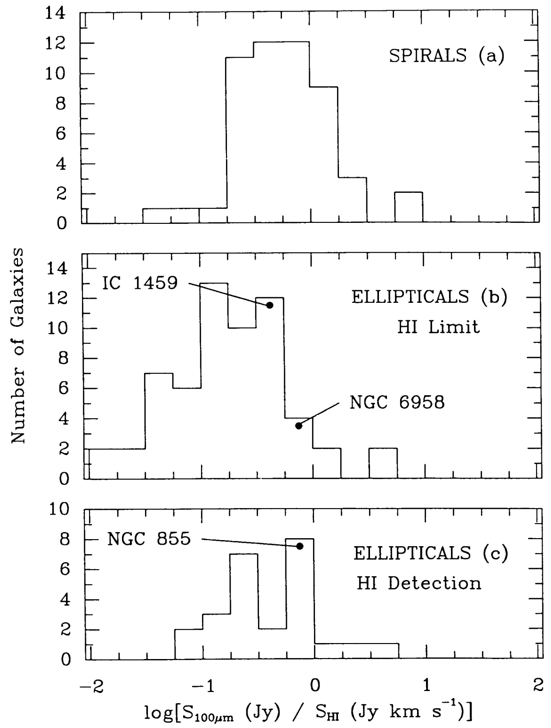

FIG. 3.—Histograms of the 100 μm—H I 21 cm line flux density ratios. The spirals in (*a*) are Sc's from the H I catalog of Huchtmeier *et al.* (1983) smaller than the *IRAS* beam (Sarlin 1988). The elliptical galaxies are from Walsh and Knapp (1989), the lower limits for the ratio for the H I nondetections are in (*b*) (using the 3 σ × 500 km s^{-1} upper limits for H I mass). The H I detections are in (*c*).

IV. IC 1459

IC 1459 is an active galaxy with radio designation PKS 2254−367 which, unlike the two other ellipticals we observed, is in a small cluster (the Grus cluster).

The nucleus is redder than the rest of the galaxy, and there is some evidence of extinction in the central 10″ (Sparks *et al.* 1985). There are several detected emission lines typical of a LINER galaxy (e.g., Sadler 1987; Phillips *et al.* 1986), and X-ray emission has also been found (Canizares, Fabbiano, and Trinchieri 1987). This is one of the first galaxies in which twisting isophotes were noticed (Williams and Schwarzschild 1979; Franx, Illingworth, and Heckman 1989). It is also the first elliptical discovered to contain a counter-rotating core (Franx and Illingworth 1988); the stars in the core rotate in a direction opposite to the main body of the galaxy and also opposite to the ionized gas in the center.

A photograph by Malin (1985) reveals what appears to be spiral structure in the outer regions of the galaxy and possible interactions with a nearby spiral, IC 5264. There are four additional spirals from the ESO catalog which were within our field of view; these are discussed in § IV*d*.

Various properties of IC 1459 are listed in Table 5 for which the optical and infrared information is drawn from the same sources as for Table 2, except for the 10 μm measurement, which was made by Sparks *et al.* (1986); this reference also gives near-IR colors and magnitudes. This 10 μm upper limit is 3 σ. The dramatic difference between this and the 12 μm *IRAS*

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TABLE 5

PREVIOUS OBSERVATIONS OF IC 1459

Parameter	Value
Optical	
B_T	10.88
$B-V$	0.99
Infrared	
Flux Density (mJy) at 10 μm	<36.6
Flux Density (mJy) at 12 μm	160
Flux Density (mJy) at 25 μm	300
Flux Density (mJy) at 60 μm	520
Flux Density (mJy) at 100 μm	1050
Radio Continuum	
Flux Density (mJy) at 2 cm	1150 ± 10
Flux Density (mJy) at 3.4 cm	580 ± 50
Flux Density (mJy) at 6 cm	1073 ± 30
Flux Density (mJy) at 11 cm	1155 ± 23
Flux Density (mJy) at 20 cm	970
Flux Density (mJy) at 73 cm	700 ± 60
H I 21 cm Line	
Mass ($M_\odot$)	$<3 \times 10^8$

detection may be caused by the larger beam size of the satellite, which was 30″ at the shorter wavelengths. The 10 μm measurement was made with a 5″ aperture. (The *IRAS* beam does not, however, encompass the nearest spiral; the 100 μm beam was 3′, and the detected source has good positional coincidence with the center of IC 1459). This would tend to suggest that the infrared emission, at least at short wavelengths, is produced on a scale much larger than ~5″ (about 400 pc), i.e., it is unlikely to be emitted by the nucleus.

a) *Radio Continuum*

In Table 5, the 2 cm observation is by Sparks *et al.* (1984), and the 3.4 cm value is given by Haynes *et al.* (1975). Both the 6 cm and 11 cm values are from Sadler (1984). The 20 cm continuum measurement is by Ekers *et al.* (1989), and the 73 cm detection is from Large *et al.* (1981). There has been a tendency for the more recent measurements to give higher flux densities (see Disney and Wall 1977). This may explain the anomalous 3.4 cm value, it being the oldest of those given in the table. Figure 4 shows the flux density of IC 1459 at infrared and radio wavelengths; apart from the 3.4 cm observation, the radio spectrum is fairly flat and at a similar level to the 100 μm flux density.

For our continuum image of IC 1459, uniform weighting was used. Our 20 cm measurement of IC 1459 is given in Table 3; none of the spiral galaxies in the field were detected as a continuum source.

b) *Neutral Hydrogen*

IC 1459 has a mass limit on its H I from Jenkins (1982) and was not detected by us in either emission or absorption, despite the presence of gas-rich neighbors. The total H I map is shown in Figure 5; crosses mark the centers of the galaxies in the field. The three detections coincide with IC 5269B, NGC 7418A, and IC 5264, all of which are spirals.

In order to calculate an upper limit to the H I mass in IC 1459, assumptions need to be made about the appropriate area and velocity range. For the limit in Table 4, a velocity of 500 km s^{-1} has been used. This is roughly twice the rotation velocity of the stars in the counter-rotating core (Franx and Illingworth 1988) and much larger than that outside this core; the velocity dispersion peaks at about 350 km s^{-1}. For the spatial distribution, it has been assumed that at each velocity the hydrogen is smoothly distributed over an area equal to four synthesized beams, and three times the rms noise of 2 mJy within this area has been used for the limit. This size is chosen because it is large enough to contain the known ionized gas and also is approximately the same as the *IRAS* 100 μm beam, which is the relevant size for a comparison with far-infrared luminosity. These assumptions lead to $M_{\rm H\,I} < 2 \times 10^8\ M_\odot$. The value that should be used for the mass within the core is half of this (i.e., the limit corresponding to one synthesized beam). Hence $M_{\rm H\,I}$(core) $< 10^8\ M_\odot$.

Figure 6 shows two line profiles for IC 1459. The dashed profile was calculated for an area of approximately two beams, while the solid line shows the recorded flux densities from an area 3′ × 3′ centered on the galaxy. The profile on this larger scale shows that no hydrogen has been clearly detected in a region comparable to the *IRAS* 100 μm beam. Hence, the upper limit from Table 4 is used in Figure 3 for the ratio of infrared luminosity to H I mass. Line profiles for the outer part of IC 1459 likewise show no evidence for emission (the feature at 1400 km s^{-1} is stronger than any farther out in the galaxy), but the H I mass limit for the whole galaxy should be taken as a few times that given above, to allow for the possibility that the hydrogen might occupy more than four synthesized beams at any velocity. It is also possible that some of the hydrogen seen near IC 5264 is bound to the elliptical rather than the spiral. (None of the small patches around IC 1459 in Figure 5 appear above a 3 σ level on more than two channel maps (Fig. 7), and none are at the assumed systemic velocity of the galaxy or either adjacent channel. The closest points, just to the north of the galaxy, are responsible for the peak in the line profile at 1400 km s^{-1}. The area under the profile for these patches (for the solid line in Fig. 6) is ~700 mJy km s^{-1}, which is equivalent to a mass of $5 \times 10^7\ M_\odot$.)

The upper limits for H I mass are slightly high. This is because the observations appear to be spectral dynamic range

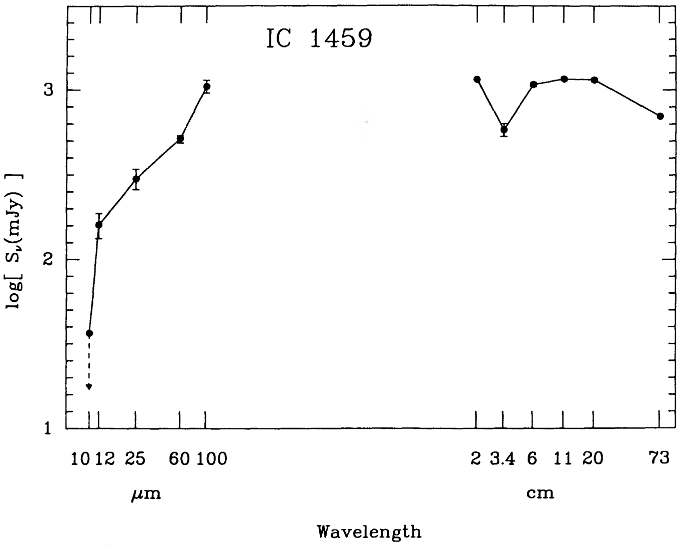

FIG. 4.—Radio and infrared spectrum for IC 1459

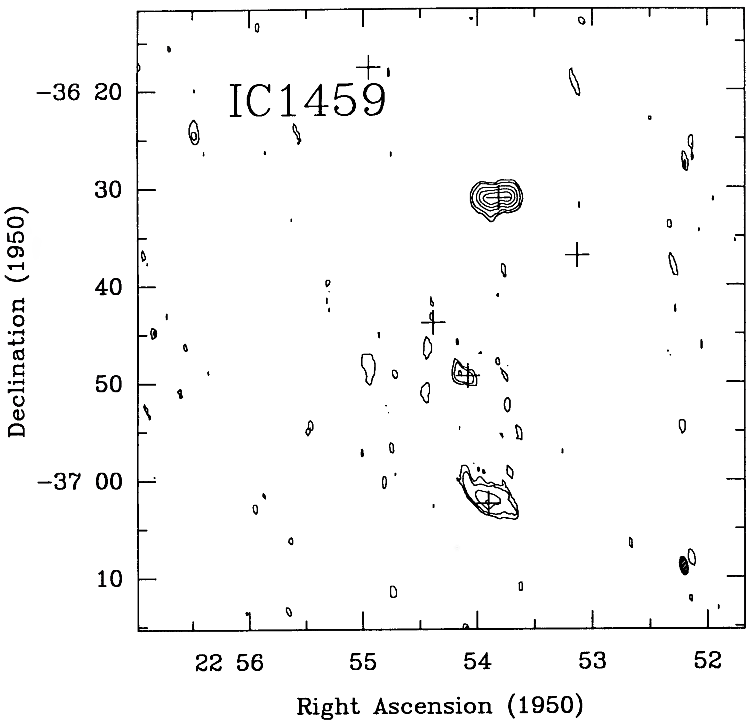

FIG. 5.—Total H I map of the region around IC 1459. Crosses mark the positions of IC 1459 (*central cross*) and the neighboring spiral galaxies. The contour levels are 5, 10, 20, 30, and 40 × 10^{19} atoms cm^{-2}. The beam is shown in the lower right.

limited. The small positive and negative patches in Figure 7 are at the level of 0.2% of the peak of the continuum intensity and cannot be trusted. In addition, our limit for the central arcminute could be affected by canceling of emission and absorption features within one beam.

Therefore, it appears possible that a few $\times 10^7\ M_\odot$ of H I may be present within a few arcminutes of the center of IC 1459, but instrumental effects and the possibility of absorption introduce much uncertainty into the mass estimate.

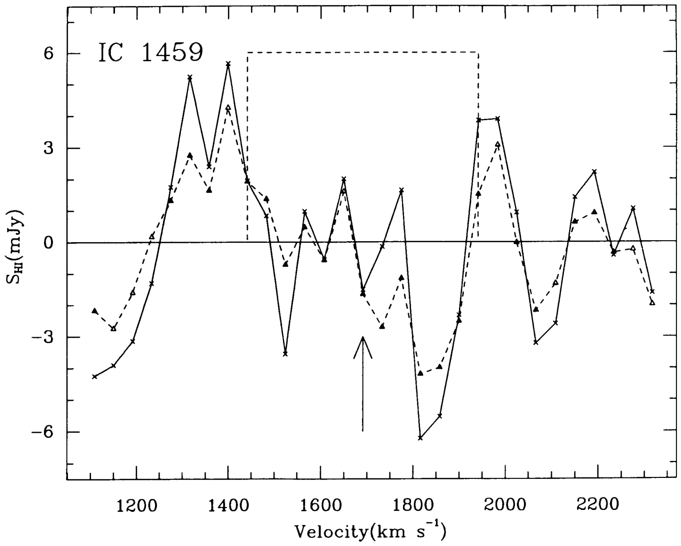

FIG. 6.—H I profiles for IC 1459. The box represents the velocity range used in calculating an upper limit to the mass. The arrow indicates the systemic velocity. The solid line gives the flux density in an area ~3′ × 3′, while the dashed line is for a size equal to two synthesized beams.

c) *Interpretation*

While the argument used for NGC 6958 that the IR could be reradiation of starlight by dust (see § V) may also be extended to IC 1459, there is another explanation which suggests itself. Golombek, Miley, and Neugebauer (1988) have reported that active galaxies are more likely to have been detected by *IRAS* than are other ellipticals, and that for those in which the radio emission is dominated by a flat-spectrum compact nuclear source, the far-infrared radiation is most plausibly explained as being nonthermal; the radio continuum extends to infrared wavelengths. IC 1459, with its powerful radio continuum, fits comfortably into this picture. It is possible that some of the infrared radiation is thermal, because the extension of the continuum is not well determined. The 100 μm/60 μm spectral index suggests some difference from the flat radio spectrum. While the straightforward extrapolation of the nonthermal radiation into the infrared is attractive, a possible counterargument in favor of star formation is the apparently extended nature of the infrared emitting source at shorter wavelengths; however, it is not necessary that the near- and far-infrared power has to come from the same region. The correlation between the strengths of the radio power and the presence of IR emission, interpreted by Golombek, Miley, and Neugebauer as indicating a nonthermal origin for the infrared, may alternatively be seen as suggesting a thermal source; the radio luminosity coming from a black hole being fueled by gas, which implies the presence of dust, hence far-infrared radiation (Walsh *et al.* 1989).

It has been suggested by Sparks, Machetto, and Golombek (1989) that heat transfer from hot X-ray gas to dust may be important in producing infrared luminosity. Such thermal conduction would also be responsible for optical emission lines. It is not clear that this model can be applied to IC 1459, which

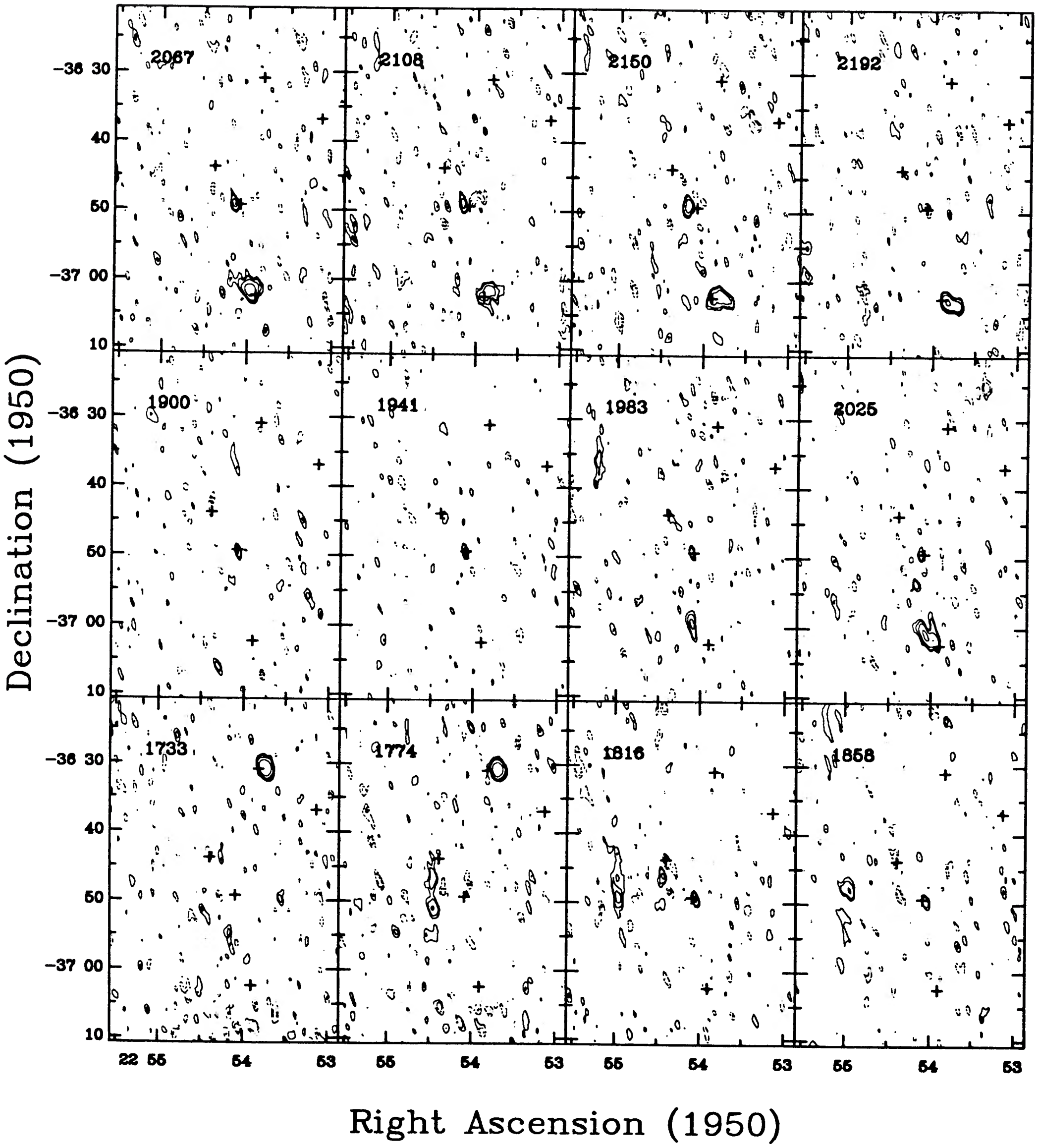

FIG. 7.—Channel maps for the region around IC 1459. The contour levels are −3, −2 (*dashed lines*), 2, 3, 5, and 10 mJy per beam. Numbers indicate velocity, crosses indicate the positions of galaxies (IC 5269 is outside the area shown).

has a powerful nonthermal radio source, indicating a strong magnetic field which could significantly alter the effectiveness of conduction. However, the sizes of the regions of extinction and of emission-line gas are similar (about 10″), perhaps indicating a connection between them. This would naturally explain the absence of H I, the gas being ionized. The presence of X-ray emission does not, however, exclude the possibility of finding neutral hydrogen (Knapp 1987).

IC 1459 illustrates an important point about galaxies experiencing mergers or tidal interactions with their neighbors. Although when H I is present in ellipticals it often seems to be of external origin, encounters do not always conspire to provide detectable amounts of neutral hydrogen.

d) *The Neighboring Spirals*

The five spirals within our field of view which are in the ESO catalog are listed, together with the information from that source, in Table 6. For the three galaxies which show up on the total H I map, the line profiles are shown in Figure 8. The derived total masses (calculated as for NGC 855) are in Table 7. For IC 5264, the figure suggests there are problems with the definition of the baseline. For the calculation of H I mass in Table 7, we assumed a "baseline" of 3 mJy, as indicated by the dashed line in the figure. The sense of rotation for this galaxy is such that high velocities are on the side nearer to IC 1459. The patches in Figure 6 between IC 5264 and NGC 7418A are not related to either galaxy, having velocities of ∼1200 km s^{-1}.

All the spirals had previously been searched for hydrogen. Aaronson *et al.* (1981) give high-velocity resolution profiles of NGC 7418A and IC 5269B. There are also very marginal detections of IC 5269A and IC 5269. Fisher and Tully (1982) find for IC 5269B a hydrogen mass of 1.2 × 10^9 $M_\odot$. Bottinelli, Gouguenheim, and Paturel (1982*a*, *b*, *c*) report the detection of IC 5264, for which they give the hydrogen mass as 1.5 × 10^9 $M_\odot$.

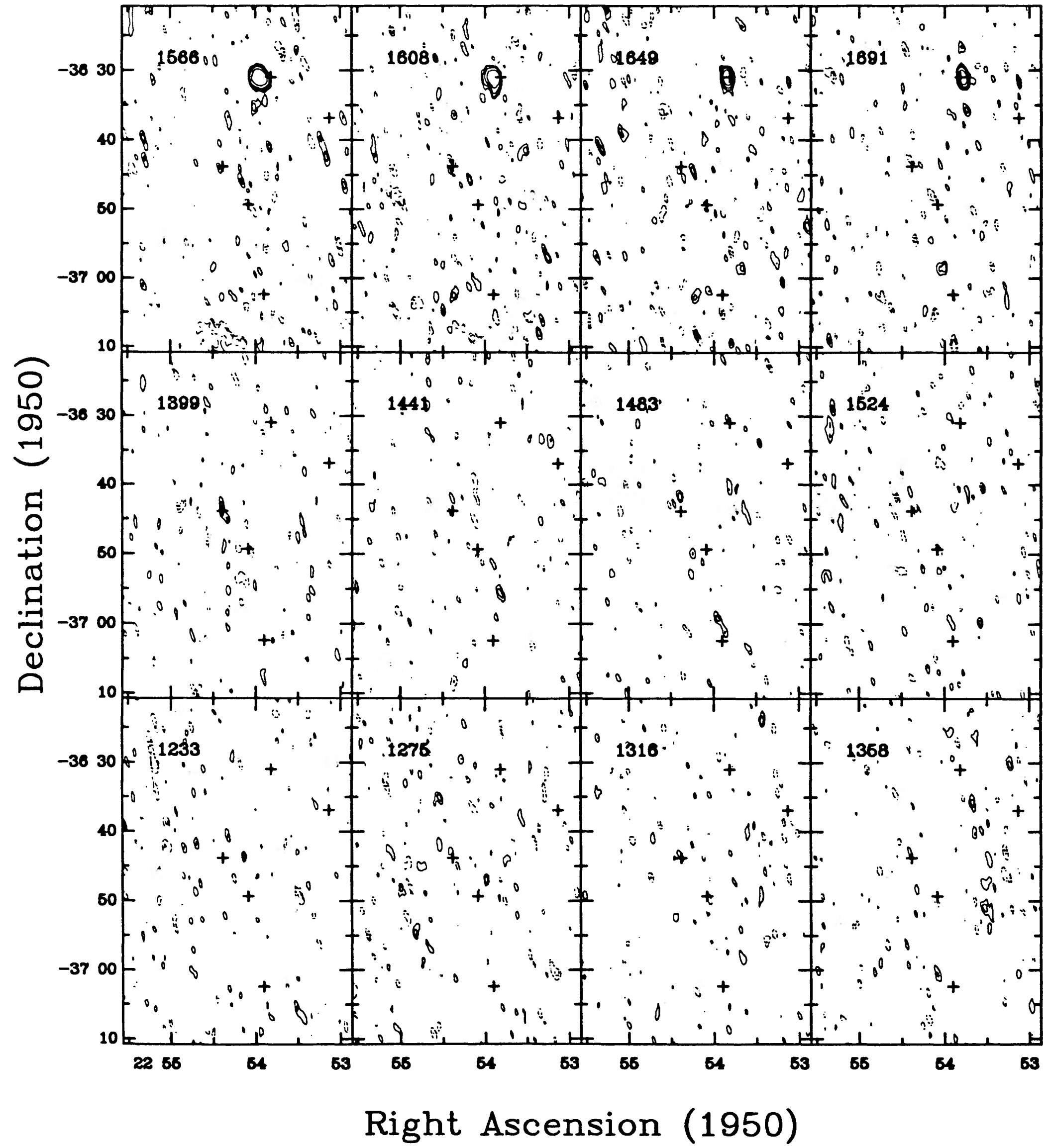

FIG. 7.—*Continued*

V. NGC 6958

Various data concerning NGC 6958 are presented in Table 8. The optical and infrared values are from the same references as in Tables 2 and 5.

In addition to the data in the table, there have been detections of dust patches and a red nucleus (Sparks *et al.* 1985). These authors attribute the color to an excess of red light rather than a lack of blue light; they also note a pronounced isophotal twist. Likewise, Veron-Cetty and Veron (1988) present CCD images which show a red nuclear region with extent 10″ × 3″.5. NGC 6958 is included in the Malin and Carter (1983) catalog of shell galaxies. A photometric map of the galaxy is shown by de Carvalho and da Costa (1988).

TABLE 6

SPIRAL GALAXIES IN THE FIELD OF IC 1459

Name	R.A.	Decl.	Size	P.A.	Velocity (km s^{-1})	Type
IC 5269A	22^{h}53^{m}08^s	−36°36′.9	1′.6 × 1′.2	35°	...	S
IC 5269B	22 53 49	−36 31.0	5.5 × 1.1	96	1659	Sc-d
NGC 7418A	22 53 54	−37 02.4	3.6 × 2.0	83	2050	Sc?
IC 5264	22 54 05	−36 49.3	2.7 × 0.6	82	2043	Sb
IC 5269	22 54 57	−36 17.6	1.8 × 0.9	51	2162	S0

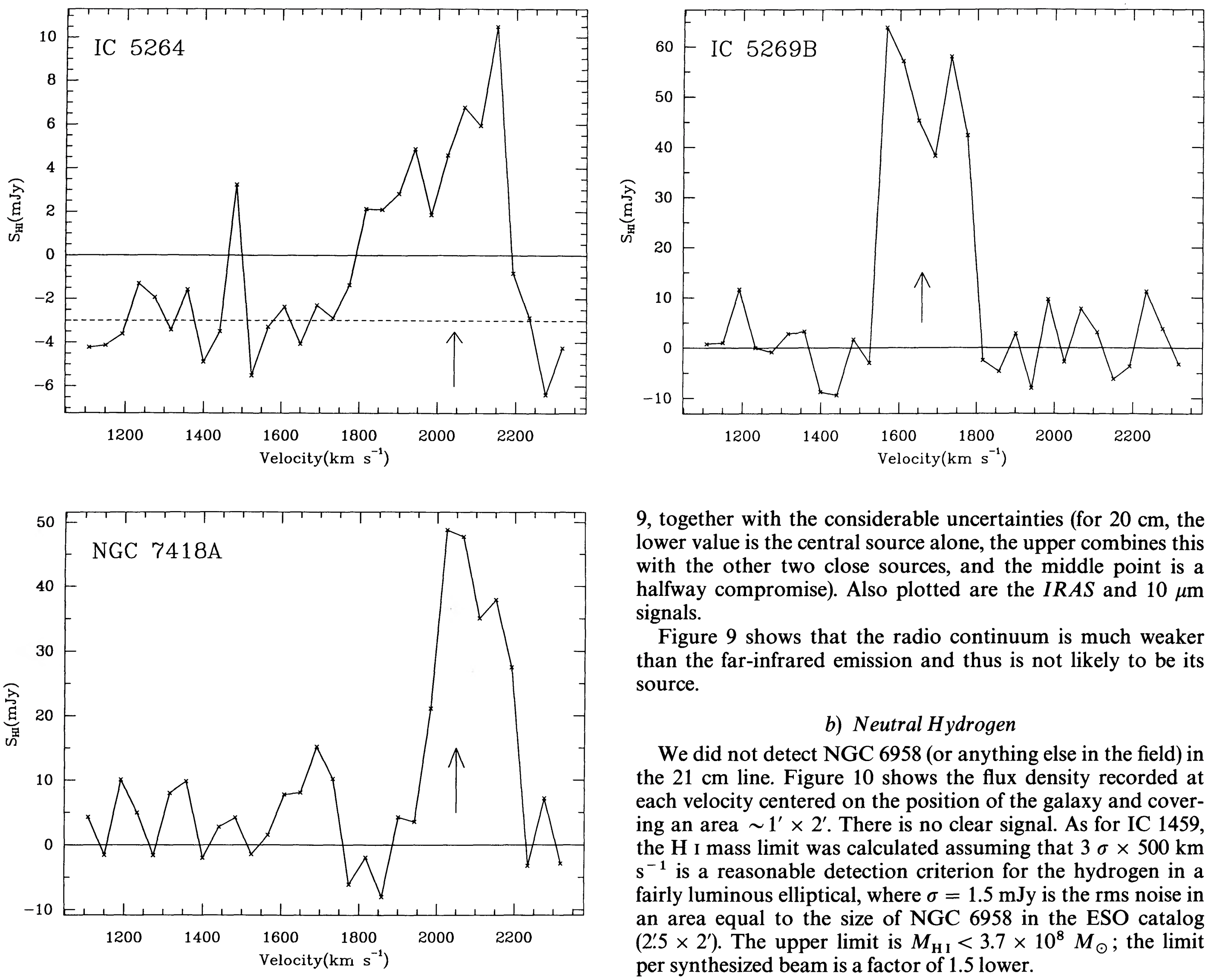

FIG. 8.—H I profiles for the detected spirals in the field of IC 1459. For IC 5264, the dashed line is the "baseline" assumed for the mass calculations—see text. Arrows show systemic velocity of the galaxies.

a) *Radio Continuum*

Table 8 lists the available radio continuum data for this galaxy. The 2 cm measurement is from Sparks *et al.* (1984), the 6 cm value is given by Sadler, Jenkins and Kotanyi (1989), and the 11 cm measurement is from Sadler (1984). Close to NGC 6958, we find two other continuum sources which may have fallen within the beam used by Sadler (1984). The flux density of the central source at each wavelength is displayed in Figure 9, together with the considerable uncertainties (for 20 cm, the lower value is the central source alone, the upper combines this with the other two close sources, and the middle point is a halfway compromise). Also plotted are the *IRAS* and 10 μm signals.

Figure 9 shows that the radio continuum is much weaker than the far-infrared emission and thus is not likely to be its source.

TABLE 7

H I MASSES OF THE SPIRAL GALAXIES

Galaxy	H I Flux (Jy km s^{-1})	Distance (Mpc)	Mass ($M_\odot$)
IC 5269B	12.6	16.6	8.2×10^8
NGC 7418B	9.3	20.5	9.2×10^8
IC 5264	1.7	20.4	2.9×10^8

b) *Neutral Hydrogen*

We did not detect NGC 6958 (or anything else in the field) in the 21 cm line. Figure 10 shows the flux density recorded at each velocity centered on the position of the galaxy and covering an area $\sim 1' \times 2'$. There is no clear signal. As for IC 1459, the H I mass limit was calculated assuming that $3\ \sigma \times 500$ km s^{-1} is a reasonable detection criterion for the hydrogen in a fairly luminous elliptical, where $\sigma = 1.5$ mJy is the rms noise in an area equal to the size of NGC 6958 in the ESO catalog ($2'.5 \times 2'$). The upper limit is $M_{\rm H\,I} < 3.7 \times 10^8\ M_\odot$; the limit per synthesized beam is a factor of 1.5 lower.

TABLE 8

PREVIOUS OBSERVATIONS OF NGC 6958

Parameter	Value
B_T	12.21
$B-V$	0.91
Infrared	
Flux Density (mJy) at 10 μm	44
Flux Density (mJy) at 12 μm	150
Flux Density (mJy) at 25 μm	200
Flux Density (mJy) at 60 μm	1090
Flux Density (mJy) at 100 μm	2020
Radio Continuum	
Flux Density (mJy) at 2 cm	23 ± 10
Flux Density (mJy) at 6 cm	18.1 ± 0.2
Flux Density (mJy) at 11 cm	43 ± 12
H I 21 cm Line	
Mass ($M_\odot$)	$<3 \times 10^8$

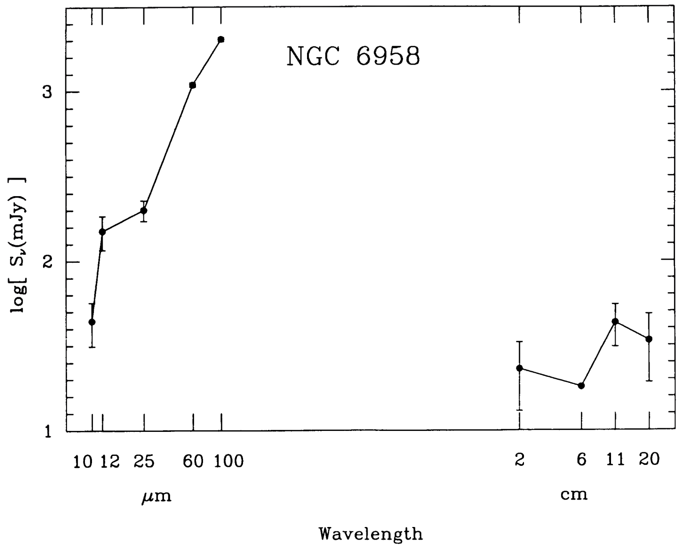

FIG. 9.—Radio and infrared spectrum for NGC 6958

c) *Interpretation*

Unlike IC 1459, the far-infrared emission in NGC 6958 is too strong to be an extension of the nonthermal radio continuum, yet there is no direct evidence for the presence of a cool gas. Indeed, the limit on the H I content and the very high 100 μm flux density give this galaxy one of the higher IR luminosity per H I mass values among E's (see Fig. 3). However, with many other lower limits for the elliptical galaxies, it is perhaps not an unusual specimen. There are also several other ellipticals with high 100 μm flux density, neutral hydrogen not detected with a sensitive limit and weak radio continuum emission, such as NGC 2783, 4476, 3842, and 4649.

In spirals, much of the scatter in the IR/H I ratio is likely to arise from varying fractions of hydrogen being in molecular form, and also from increased IR emission associated with star formation. In ellipticals, a more likely cause for a high value of this quantity is an intense radiation field heating the dust grains. The far-infrared color may be used to estimate the temperature of the grains and hence the strength of the radiation field. However, the temperature is difficult to determine accurately, and the derived intensity of the radiation field is exponentially sensitive to it. (Problems in deciding the appropriate temperature include the unknown emissivity of the dust grains and the possibility that some of the 60 μm luminosity derives from small grains; see Draine and Anderson 1985.) While there are considerable uncertainties, Jura (1986) provides a prescription for calculating the dust mass needed to produce the measured infrared flux by assuming an opacity for this dust and a radiation field compatible with the color temperature. The formula yields $M_{\rm dust} \sim 2.5 \times 10^6\ M_\odot$. It therefore appears that should the gas-to-dust mass ratio be similar to the local value of ~100, the required amount of hydrogen is marginally consistent with our upper limit. A higher temperature than the 20 K used would make the limit more comfortable.

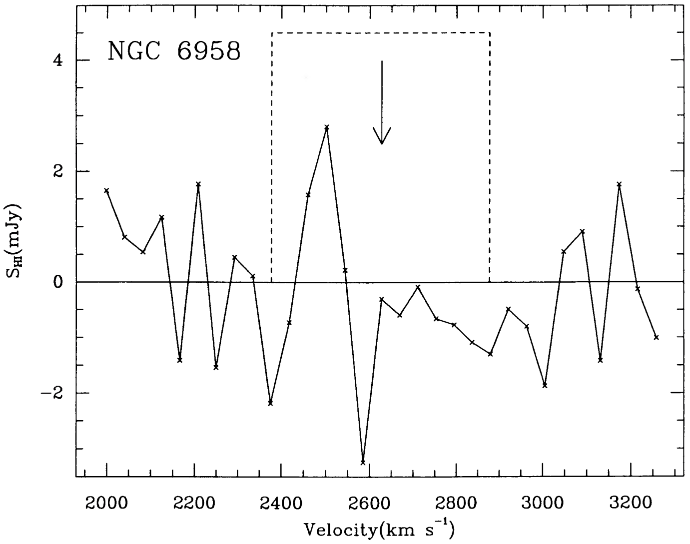

FIG. 10.—H I line profile for NGC 6958. The box represents the velocity range used in calculating the mass limit, and the arrow shows the galaxy's velocity.

Brosch (1987) has questioned whether the temperatures indicated by the 100 μm and 60 μm flux densities can be produced by elliptical galaxies. Using the same model as incorporated in Jura's formula, he found it necessary to concentrate the dust in the inner parts (~1 kpc) of the galaxies, where the radiation field is strongest. Since the infrared luminosity of NGC 6958 is ~30% of the total blue luminosity, if the IR is originating from a small region, the dust must be intercepting a considerable fraction of the incident light and might be detectable in absorption. The size of the red nucleus shown by Veron-Cetty and Veron (1988) and by Sparks *et al.* (1985) is appropriate for a candidate for such absorption, although it is not clear that the red color is a signature of a deficit of blue light or an excess of red light.

Cen A has the highest IR/H I ratio among ellipticals in Figure 3; it is also one of the very few ellipticals where there is known to be molecular gas. Is it possible that other elliptical galaxies have much molecular gas? To estimate the "expected" H_2 mass in NGC 6958, a $L_{\rm IR}/M_{\rm H_2}$ ratio of ~6 in solar units will be used (Sanders and Mirabel 1985). This value is obtained for molecular clouds in late-type spirals, and its applicability must be considered dubious at best. The inferred mass is $M_{\rm H_2} \sim 6 \times 10^8\ M_\odot$. Adopting $M_{\rm H_2} = 5.8 L_{\rm CO}$ (K km s^{-1} pc^2) (Scoville and Sanders 1987) leads to a CO luminosity of ~10^8 K km s^{-1} pc^2, and at the distance of NGC 6958, the beam area is ~$2 \times 10^8 (\theta')^2$ pc^2, with θ' the beam size in arcminutes. It is therefore potentially detectable.

A high infrared luminosity per H I mass is also attainable through star formation (the IR luminosity only requires this to be happening on a low level). Unlike NGC 855, NGC 6958 is not a dwarf, and a small amount of star formation would not be expected to produce a $B-V$ color unusually blue for an elliptical. The far-infrared to blue luminosity ratio is lower in NGC 6958, so that the fraction of mass presently engaged in forming stars would be small. However, the existence of several other galaxies with similar H I, IR, and radio continuum properties to NGC 6958 indicates that the production of infrared emission does not represent a short-lived episode. Hence, the cumulative effects of overproducing young stars might become a problem unless the IR luminosity per newly formed star is high. The data corroborating the star formation hypothesis for NGC 855 are from high-resolution images, and it is a nearby galaxy, an advantage when looking for fairly small features such as molecular cloud–H II complexes. It is therefore not surprising that morphological evidence for putative star-forming regions does not exist for NGC 6958.

One of the best indicators of star formation in spiral galaxies is the radio continuum/IR luminosity ratio; but the standard (Wunderlich, Klein, and Wielebinski 1987) value for this requires only that the 6 cm flux density be 3 mJy for NGC 6958. Since $S_{6\ \mathrm{cm}}$ is several times this, it is possible that the IR emission is the product of star formation (with an excess of radio continuum emission from another source). This argument may be extended to all ellipticals, because they, like NGC 6958, have an "excess" of radio power.

The near-infrared colors (Sparks *et al.* 1986; also Persson, Frogel, and Aaronson 1979) are probably stellar (M giant) in origin, although there may be a slight excess in the *N* band (10 μm). However, this is more characteristic of LINER galaxies than either starbursts or extragalactic H II regions (Lawrence *et al.* 1985). The LINER nature of NGC 6958 is also mentioned by Phillips *et al.* (1986) and by Caldwell (1984), who give line widths for [N II] $\lambda6584$ and [O II] $\lambda3727$. Caldwell also uses the Hα flux to derive a mass in ionized gas $\leq 10^4\ M_\odot$. This exists in a region small compared to the extent of the red nucleus.

In summary, the simplest explanation for the H I nondetection of this *IRAS* bright galaxy is that the ambient interstellar radiation field is warm and thus enables a small mass of dust to suffice in producing the IR luminosity within the VLA constraints on the gas content. However, hiding hydrogen in molecular form could also do the trick and may imply a detectable level of CO. Star formation is a third possibility.

VI. CONCLUSION

The main findings from these VLA observations are that the detection of an elliptical galaxy in the far-infrared by *IRAS* does not signify that a substantial cool ISM is present; neither is there a unique mechanism for producing apparently similar IR colors. Moreover, the three galaxies studied have nothing unusual in their IR colors to indicate they are special cases, but we find three quite different origins for this luminosity. While the two H I nondetected galaxies we observed did have *IRAS* 12 and 25 μm detections and NGC 855 did not, this is not generally true of elliptical galaxies (Walsh and Knapp 1989). It is true that the majority of neutral hydrogen detections are for galaxies possessing high infrared flux densities, but this is due at least in part to the small distance of these apparently strong sources.

Star formation provides the heating for the dust in NGC 855 which is responsible for the far-infrared luminosity; the grains are not just immersed in the ambient radiation field. The radio continuum–far-infrared flux density ratio is similar to that which holds for spirals and even starburst galaxies, but NGC 855 is a dwarf elliptical with no stellar disk and not much ISM. This suggests the ratio and star formation rate are determined on a small scale.

A very different origin for far-infrared emission is an extension of the radio continuum to these shorter wavelengths, so that the luminosity is not thermal. IC 1459 is a case in point; this possibility has been discussed by Golombek, Miley, and Neugebauer (1988). Hence, an *IRAS* detection need not imply the presence of a cool interstellar medium. It is, however, quite possible that some of the IR flux is from dust, because the "expected" contribution from the nuclear source is not well determined.

NGC 6958 is not a candidate for this nonthermal mechanism for producing the IR, having too weak a radio continuum. Neither is there any evidence for star formation (but this is not impossible). Dust reemitting the starlight forming the interstellar radiation field may be a viable means of providing NGC 6958 with its IR luminosity. However, an intense radiation field (relative to that in the galaxy) is needed to alleviate the problem of the small ISM mass available when constrained by the H I observations. Therefore, while the *IRAS* data here may indicate a cool ISM, the derivation of its mass needs some assumption regarding the heating of the grains. Specifically, this problem may be parameterized in terms of the temperature of the resultant IR flux (once a model for the dust properties has been chosen). Unfortunately, this temperature is difficult to gauge accurately just from the color temperature of the long-wavelength IR radiation, and the required mass is very sensitive to the value used; its accurate estimation is thus problematical.

Another possible remedy for the high IR/$M_{\mathrm{H\,I}}$ observed is to hide the hydrogen as molecules. If the mass-to-infrared luminosity ratio applicable to the component clouds of spirals is a meaningful indicator, this quantity of molecular gas should yield detectable amounts of CO in the strongest 100 μm sources, such as NGC 6958.

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REFERENCES

Aaronson, M., Dawe, J. A., Dickens, R. J., Mould, J. R., and Murray, J. B. 1981, *M.N.R.A.S.*, **195**, 1p.
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., and Witzel, A. 1977, *Astr. Ap.*, **61**, 99.
Bottinelli, L., Gouguenheim, L., and Paturel, G. 1982, *Astr. Ap. Suppl.*, **47**, 171.
———. 1982, *Astr. Ap. Suppl.*, **50**, 101.
———. 1982, *Astr. Ap.*, **113**, 61.
Brosch, N. 1987, *M.N.R.A.S.*, **225**, 257.
Burstein, D., Davies, R. L., Dressler, A., Faber, S. M., Stone, R. P. S., Lynden-Bell, D., Terlevich, R. J., and Wegner, G. 1987, *Ap. J. Suppl.*, **64**, 601.
Caldwell, N. 1984, *Pub. A.S.P.*, **96**, 287.
Canizares, C. R., Fabbiano, G., and Trinchieri, G. 1987, *Ap. J.*, **312**, 503.
de Carvalho, R. R., and da Costa, L. N. 1988, *Ap. J. Suppl.*, **68**, 173.
Devereux, N. A., and Eales, S. A. 1989, *Ap. J.*, **340**, 708.
Disney, M. J., and Wall, J. V. 1977, *M.N.R.A.S.*, **179**, 235.
Draine, B. T., and Anderson, N. 1985, *Ap. J.*, **292**, 494.
Dressel, L. L., and Condon, J. J. 1978, *Ap. J. Suppl.*, **36**, 53.
Ebneter, K., Djorgovski, S., and Davis, M. 1988, *Ap. J.*, **95**, 422.
Ekers, R. D., *et al.* 1989, *M.N.R.A.S.*, **236**, 737.
Fisher, J. R., and Tully, R. B. 1981, *Ap. J. Suppl.*, **47**, 139.
Franx, M., and Illingworth, G. 1988, *Ap. J. (Letters)*, **327**, L55.
Franx, M., Illingworth, G., and Heckman, T. 1989, *Ap. J.*, **344**, 613.
Golombek, D., Miley, G. K., and Neugebauer, G. 1988, *A.J.*, **95**, 26.
Haynes, R. F., Huchtmeier, W. K. H., Siegman, B. C., and Wright, A. E. 1975, *A Compendium of Radio Measurements of Bright Galaxies* (Sydney: CSIRO Division of Radiophysics).
Huchtmeier, W. K., Richter, O. G., Bohnenstengel, H. D., and Hauschildt, M. 1983, ESO preprint 250.
Jenkins, C. 1982, *M.N.R.A.S.*, **205**, 1321.
Jura, M. 1986, *Ap. J.*, **306**, 483.
Kim, D. W., Guhathakurta, P., van Gorkom, J. H., Jura, M., and Knapp, G. R. 1988, *Ap. J.*, **330**, 684.
Knapp, G. R. 1987, in *IAU Symposium 127, Structure and Dynamics of Elliptical Galaxies*, ed. T. de Zeeuw (Dordrecht: Reidel), p. 145.
Knapp, G. R., Guhathakurta, P., Kim, D. W., and Jura, M. 1989, *Ap. J. Suppl.*, **70**, 329.
Knapp, G. R., Turner, E. L., and Cunniffe, P. E. 1985, *A.J.*, **90**, 454.
Lake, G., Schommer, R. A., and van Gorkom, J. H. 1987, *Ap. J.*, **314**, 57.
Large, M. I., Mills, B. Y., Little, A. G., Crawford, D. F., and Sutton, J. M. 1981, *M.N.R.A.S.*, **194**, 693.

Lauberts, A. 1982, *ESO/Uppsala Catalogue of the ESO-B Sky Survey* (Munich: European Southern Observatory).
Lawrence, A., Ward, M., Elvis, M., Fabbiano, G., Willner, S. P., Carleton, N. P., and Longmore, A. 1985, *Ap. J.*, **291**, 117.
Malin, D. F. 1985, in *New Aspects of Galaxy Photometry*, ed. J. L. Nieto (Berlin: Springer-Verlag), p. 27.
Malin, D. F., and Carter, D. 1983, *Ap. J.*, **274**, 534.
Marston, A. P. 1988, *M.N.R.A.S.*, **231**, 333.
Persson, C. J., and Helou, G. 1987, in *Star Formation in Galaxies*, ed. C. J. Lonsdale Persson (NASA CP-2466), p. 153.
Persson, S. E., Frogel, J. A., and Aaronson, M. 1979, *Ap. J. Suppl.*, **39**, 61.
Phillips, M. M., Jenkins, C. R., Dopita, M. A., Sadler, E. M., and Binette, L. 1986, *A.J.*, **91**, 1062.
Raimond, E., Faber, S. M., Gallagher, J. S., and Knapp, G. R. 1981, *Ap. J.*, **246**, 708.
Sadler, E. M. 1984, *A.J.*, **89**, 53.
———. 1987, in *IAU Symposium 127, Structure and Dynamics of Elliptical Galaxies*, ed. T. de Zeeuw (Dordrecht: Reidel), p. 125.
Sadler, E. M., and Gerhard, O. E. 1985, *M.N.R.A.S.*, **214**, 177.
Sadler, E. M., Jenkins, C. R., and Kotanyi, C. G. 1989, *M.N.R.A.S.*, **240**, 591.
Sanders, D. B., and Mirabel, I. F. 1985, *Ap. J. (Letters)*, **298**, L31.
Sarlin, S. 1988, unpublished.
Scoville, N. Z., and Sanders, D. B. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach, and H. A. Thronson (Dordrecht: Reidel), p. 21.
Sparks, W. B., Disney, M. J., Wall, J. V., and Rodgers, A. W. 1984, *M.N.R.A.S.*, **207**, 445.
Sparks, W. B., Hough, J. H., Axon, D. J., and Bailey, J. 1986, *M.N.R.A.S.*, **218**, 429.
Sparks, W. B., Macchetto, F., and Golombek, D. 1989, *Ap. J.*, **345**, 153.
Sparks, W. B., Wall, J. V., Thorne, D. J., Jorden, P. R., van Breda, I. G., Rudd, P. J., and Jorgensen, H. E. 1985, *M.N.R.A.S.*, **217**, 87.
Unger, S. W., Wolstencroft, R. D., Pedlar, A., Savage, A., Clowes, R. G., Leggett, S. K., and Parker, Q. A. 1989, *M.N.R.A.S.*, **236**, 425.
van Gorkom, J. H., Knapp, G. R., Raimond, E., Faber, S. M., and Gallagher, J. S. 1986, *A.J.*, **91**, 791.
Veron-Cetty, M. P., and Veron, P. 1988, *Astr. Ap.*, **204**, 28.
Wallington, S., Katz, N. S., Gunn, J. E., Knapp, G. R., and van Gorkom, J. H. 1989, in preparation.
Walsh, D. E. P., and Knapp, G. R. 1989, in preparation.
Walsh, D. E. P., Knapp, G. R., Wrobel, J. M., and Kim, D. W. 1989, *Ap. J.*, **337**, 209.
Williams, T. B., and Schwarzschild, M. 1979, *Ap. J.*, **227**, 56.
Wrobel, J. M., and Heeschen, D. S. 1988, *Ap. J. (Letters)*, **335**, 677.
———. 1989, in preparation.
Wunderlich, E., Klein, U., and Wielebinski, R. 1987, *Astr. Ap. Suppl.*, **69**, 487.
Young, J. S. 1987, in *Star Formation in Galaxies*, ed. C. J. Lonsdale Persson (NASA CP-2466), p. 197.

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