

THE BARRED SPIRAL GALAXY NGC 3992: DOES IT HAVE A MASSIVE HALO?¹

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ABSTRACT

We present new high-resolution H I observations of the barred spiral galaxy NGC 3992 and three nearby satellite systems. These data are employed to estimate the mass and mass distribution of NGC 3992. From an analysis of the rotation velocities we find the disk mass is most probably $2 \times 10^{11} M_{\odot}$, within a radius of 19.7 kpc. The motions of the satellites will not allow a mass greater than about $4 \times 10^{11} M_{\odot}$ within a mean radius of 59 kpc. However, we believe this to be an overestimate, perhaps by as much as a factor of 2. We conclude that (1) beyond the optical disk, the mass of the system does not increase linearly with distance, and (2) the galaxy is unlikely to possess a massive ($\sim 10^{12} M_{\odot}$) halo. This leaves open the question of why the galaxy has such a flat rotation curve.

Subject headings: galaxies: clusters of — galaxies: individual — galaxies: internal motions — galaxies: structure

I. INTRODUCTION

NGC 3992 is an exquisite example of a large, symmetric barred spiral galaxy (a good photograph is to be found in Sandage and Tammann 1981). Owing to its outstanding characteristics, it was the first system we observed at the Very Large Array (VLA) in a combined radio, optical, and theoretical study of barred spiral galaxies. The neutral hydrogen emission was observed with an effective resolution of $\sim 19''$ and a velocity resolution of 25 km s^{-1} . The distance to this system that we have adopted is 14.2 Mpc (de Vaucouleurs 1979).

Serendipitously, we observed emission from three nearby dwarf systems UGC 6923, 6940, and 6969. These appear to be Magellanic Cloud-like satellites to the more massive barred system. Thus, we are presented with an unusual opportunity not only to calculate the mass of NGC 3992 but also to estimate the extent of any massive halo it may possess. Bahcall and Tremaine (1981) have previously discussed the method with regard to M31, M101, and 3C 273. Our data offer several advantages over earlier efforts: The systemic velocities are known to at least $\pm 10 \text{ km s}^{-1}$, the Doppler width of the observed global emission profile of the galaxian neutral hydrogen enables an independent estimate of the mass of each of the galaxies, and the high-resolution ($\sim 1.3 \text{ kpc}$) observations of NGC 3992 allow its rotation velocities to be obtained and therefore its dynamics to be explored. Thus it is the purpose of this note to consider the mass of NGC 3992 as inferred from these new data. The structure, kinematics, and dynamics of the galaxy will be considered in a later publication. In the next section we will discuss the observations. In § III we consider the dynamics of the group, and we summarize our conclusions in § IV.

II. OBSERVATIONS AND DATA REDUCTIONS

The $\lambda 21 \text{ cm}$ neutral hydrogen emission from the galaxy NGC 3992, which is classified SBT4, was observed on 1980 December 16 at the VLA facility of the National Radio Astronomy Observatory at Socorro, New Mexico.² Sixteen antennas were used, yielding 120 interferometer pairs and 32 independent frequencies. The data were calibrated by observing the nearby unresolved continuum source 1311+678 every 30 minutes. The flux density of this source and the instrumental bandpass were calibrated, in turn, by several observations of the primary standard 3C 286. The single channel resolution was 25.5 km s^{-1} , with each of the 32 channels separated by 20.7 km s^{-1} . The galaxy was observed for 12 hours, and a sensitivity of 1.5 mJy per beam was achieved in each channel. The antennas were chosen to allow a fairly uniform sampling of the complex brightness visibilities from about 70 m ($\sim 330\lambda$) to about 3400 m ($\sim 16,000\lambda$). Thus spatial frequency components greater than $\sim 10'$ will be completely missing from these data.

Before this material could be Fourier inverted, four continuum sources were subtracted from the visibilities. The positions and flux densities of these sources are given in Table 1. After this correction, the data were Fourier-transformed into 32 independent brightness maps. Those maps were then "CLEANED" to remove any residual confusion caused by side lobes or grating responses (Högbom 1974). The effective resolution of these data, after tapering the visibilities and cleaning, was $18''$.

An example of one of these maps at a velocity of 1136 km s^{-1} is shown in Figure 1 (Plate 1) in which the H I emission is superposed upon the Palomar

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TABLE 1
CONTINUUM SOURCES IN THE FIELD OF NGC 3992

Source	Position (1950.0)	Flux Density (mJy) ^a
1	$\alpha 11^{\text{h}}54^{\text{m}}36^{\text{s}}.52 \pm 0^{\text{s}}.03$ $\delta 53^{\circ}35'15''.8 \pm 0''.3$	4.1 ± 0.1
2	$\alpha 11^{\text{h}}55^{\text{m}}05^{\text{s}}.11 \pm 0^{\text{s}}.04$ $\delta 53^{\circ}44'58''.0 \pm 0''.4$	6.4 ± 0.3
3 ^b	$\alpha 11^{\text{h}}55^{\text{m}}12^{\text{s}}.211 \pm 0^{\text{s}}.008$ $\delta 53^{\circ}53'10''.22 \pm 0''.07$	58.1 ± 0.4
4	$\alpha 11^{\text{h}}55^{\text{m}}47^{\text{s}}.841 \pm 0^{\text{s}}.008^{\text{c}}$ $\delta 53^{\circ}43'13''.98 \pm 0''.08$	$16.5 \pm 0.3^{\text{c}}$

^a The flux densities have not been corrected for the directivity of the antennas. The center of the synthesized field was $\alpha_{1950} 11^{\text{h}}55^{\text{m}}01^{\text{s}}.0$, $\delta_{1950} 53^{\circ}39'13''.0$.
^b This source may be slightly extended.
^c All errors are measures of internal consistency only.

Observatory Sky Survey photograph of the system. Emission can be seen from UGC 6923, UGC 6937, (NGC 3992), UGC 6940, and UGC 6969. No evidence of bridges, counterarms, or jets were found in the data at a level that would be expected, for example, from an interaction similar to that between M81, M82, and NGC 3077 (Gottesman and Weliachew 1977). No emission within a velocity range of 742–1363 km s^{−1} was observed above our sensitivity level from other objects within 30' of NGC 3992. In Figure 2 we display global emission profiles for the dwarf galaxies. The flux scale is provisional, but this uncertainty does not affect the determination of the line centers and widths given in Table 2. Global profiles for NGC 3992 can be seen in Shostak (1978) and Rots (1980). In Table 2 we list the parameters of importance for these four galaxies. In order to allow comparisons to be made with these data we have followed Shostak's precepts and have calculated indicative total masses for the four galaxies.

A flux-weighted average velocity ($\bar{V}$) for NGC 3992 can be calculated from the single channel maps of the atomic hydrogen, viz.

$$\bar{V} = \int_{-\infty}^{+\infty} S(x, y)V(x, y)dV / \int_{-\infty}^{+\infty} S(x, y)dV. \quad (1)$$

The procedure followed was similar to that employed for NGC 3359 (Gottesman 1982). The spectra within the galaxy were examined individually, and velocity limits to define the H I emission extent were determined.

Once the velocity field is established, symmetry constraints can be used to determine the inclination of the galaxy, the position angle of the line of nodes, and the systemic velocity (Gottesman 1980). The values found are given in Table 3. The observed velocity

$$V_{\text{obs}} = V_{\text{rot}}(R) \cos \theta \sin i + V_{\text{sys}} \quad (2)$$

is a function of the rotation velocity (V_{rot}), the azimuth, (θ) in the disk of the galaxy, of the point observed with respect to the line of the nodes and the inclination (i). Thus, one can invert equation (2) and establish $V_{\text{rot}}(R)$ once the symmetry parameters are known. Figure 3 shows the observed rotation velocities obtained in this fashion, by reflecting the data into the galactic disk and averaging in annuli 9".75 in radial thickness. Data within the inner ~1' have a low signal-to-noise ratio, and we have not shown the measured values. In the next section we will apply this material to the question of the mass of NGC 3992.

III. DYNAMICAL INTERPRETATION OF THE OBSERVATIONS

The most obvious hypothesis is that the smaller galaxies are satellites and are moving in bound orbits about the primary galaxy, NGC 3992. From an inspection of the projected separations of the objects (see

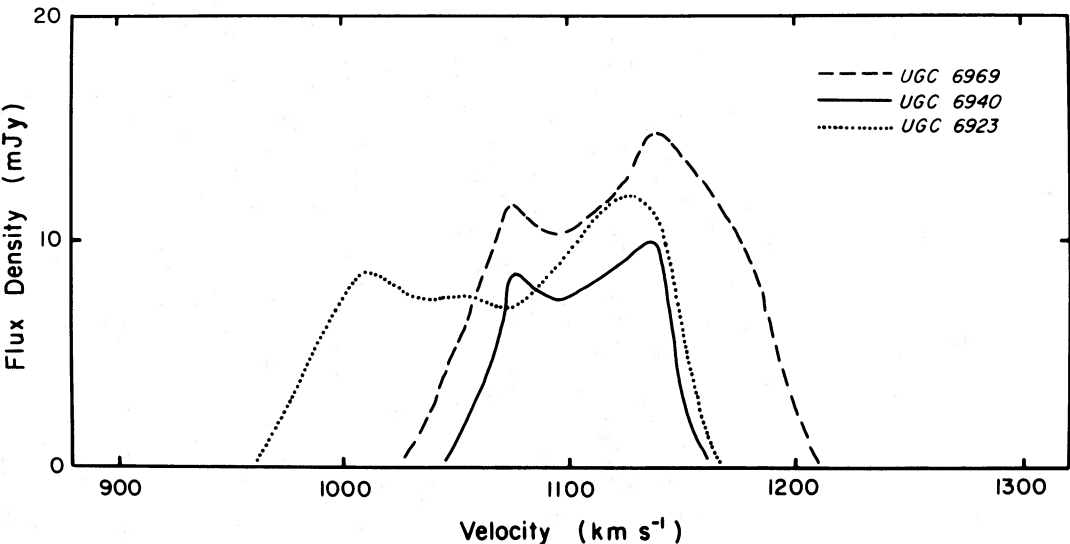


FIG. 2.—Global profiles of the atomic hydrogen emission from the three dwarf galaxies UGC 6923, 6940, and 6969. The fluxes are provisional.

TABLE 2
SYSTEMIC PARAMETERS FOR THE NGC 3992 GROUP

Object (1)	$D(0)$ ($'$) (2)	$A(0)$ (kpc) (3)	V_{sys} (km s^{-1}) (4)	ΔV (km s^{-1}) (5)	ΔV_0 (km s^{-1}) (6)	M_I ($10^{10} M_\odot$) (7)
UGC 6923	1.82	7.52	1066	186	199	0.71
UGC 6937	6.76	28.1	1050	470	560	22
(NGC 3992)						
UGC 6940	0.719	2.97	1104	97	97	0.069
UGC 6969	1.35	5.58	1110	157	163	0.36

Col. (1): UGC identification of galaxy.
Col. (2): Photometric diameter from de Vaucouleurs *et al.* 1976.
Col. (3): Linear diameter, assuming a distance of 14.2 Mpc.
Col. (4): Systemic velocity.
Col. (5): Observed global profile width measured at the 20% level. The value for NGC 3992 was taken from Rots 1980.
Col. (6): Intrinsic profile width correcting for inclination following Shostak 1978, except for NGC 3992 for which i was taken from Table 3.
Col. (7): Indicative mass, following Shostak.

Fig. 1), as well as from the indicative Brandt masses quoted in Table 2, it is obvious that the satellites contribute only very little to the mass of the system, and that the gravitational interactions of the satellites with NGC 3992 are much larger than those of the satellites upon each other. Letting S denote the projected separation in kpc of a satellite from the primary, NGC 3992, and denoting the systemic velocity difference between the objects in km s^{-1} by δV , the sum of their masses in solar units $M > q = 2.325 \times 10^5 (\delta V)^2 S$. In Table 4 we summarize additional data for the satellites, as well as the q values calculated for each satellite.

Inasmuch as the orbits would be noncircular, and the actual values δV_0 and S_0 , are larger than those quoted above due to projection factors, $M_{3992} > q$. If we ignore the projection factors for the moment and assume, as is likely, that the satellites are near apogalacticon (where they must reside most of the time), then each q value must be increased by a factor of $(1 - e)^{-1}$ where e is the orbital eccentricity. Following Bahcall and Tremaine (1981), we adopt $e = 0.7$ as typical. Hence, $M_{3992} > 3q$. Furthermore, after allowing for uncertainties in the projection factors (particularly in the velocity vectors), we do not consider it unreasonable to augment the average q value of Table 4 by a factor of 10 in order to arrive at a more realistic estimate for M_{3992} . Thus, our best guess is that $M_{3992} \approx 2.2 \times 10^{11} M_\odot$. Alternatively,

if we adopt the quantitative statistical approach of Bahcall and Tremaine (1981), then

$$M_{3992} = \frac{24}{\pi} (2.325 \times 10^5)^{\frac{1}{3}} \frac{1}{3} \sum_{i=1}^3 (\delta V_i)^2 S_i$$
$$= 1.64 \times 10^{11} M_\odot,$$

which is closely similar to our less rigorous estimate. It should be emphasized that the dynamical mass obtained from the satellite data represents the mass interior to a mean radial distance of 59 kpc, after allowing for projection effects. This should include, therefore, a substantial contribution from any halo.

Bahcall and Tremaine note that their mass estimator has a relative rms error of $1.4n^{-1/2}$ or $\sim 81\%$ for the case of three satellites. Therefore the mass could be as large as $3.0 \times 10^{11} M_\odot$. There are uncertainties also in δV of $\pm 10 \text{ km s}^{-1}$. Thus a conservative estimate of the upper limit to the mass of the galaxy from this source of error is $2.4 \times 10^{11} M_\odot$. Considering these errors, we believe that the upper limit allowed by our observations to the mass of NGC 3992 (within a radius of 59 kpc) is $4 \times 10^{11} M_\odot$.

Shostak gives the corrected blue magnitude of NGC 3992 as 10.22 mag. Adopting an absolute blue magnitude for the Sun of +5.48 (Allen 1973), we obtain a luminosity of $2.6 \times 10^{10} L_\odot$. Therefore, the mass-

TABLE 3
ROTATION PARAMETERS FOR NGC 3992

Systemic Velocity, V_{sys}	$1050 \text{ km s}^{-1} \pm 5 \text{ km s}^{-1}$
Position angle of the nodes	$67^\circ \pm 1^\circ 5'$
Inclination angle of the disk, i	$57^\circ \pm 1^\circ 5'$
Maximum rotation velocity, V_{max}	$267 \text{ km s}^{-1} \pm 5 \text{ km s}^{-1}$
Radius of maximum velocity, R_{max}	2.83 ± 0.5
Brandt law shape parameter, n	$1.0_{-0.5}^{+1.0}$

TABLE 4
LOWER LIMITS FOR THE MASS OF NGC 3992 AS
CALCULATED FROM ITS SATELLITES

Object	δV (km s^{-1})	S (kpc)	q ($10^{10} M_\odot$)
UGC 6969	60	44.2	3.7
UGC 6940	54	34.7	2.4
UGC 6923	16	59.5	0.35

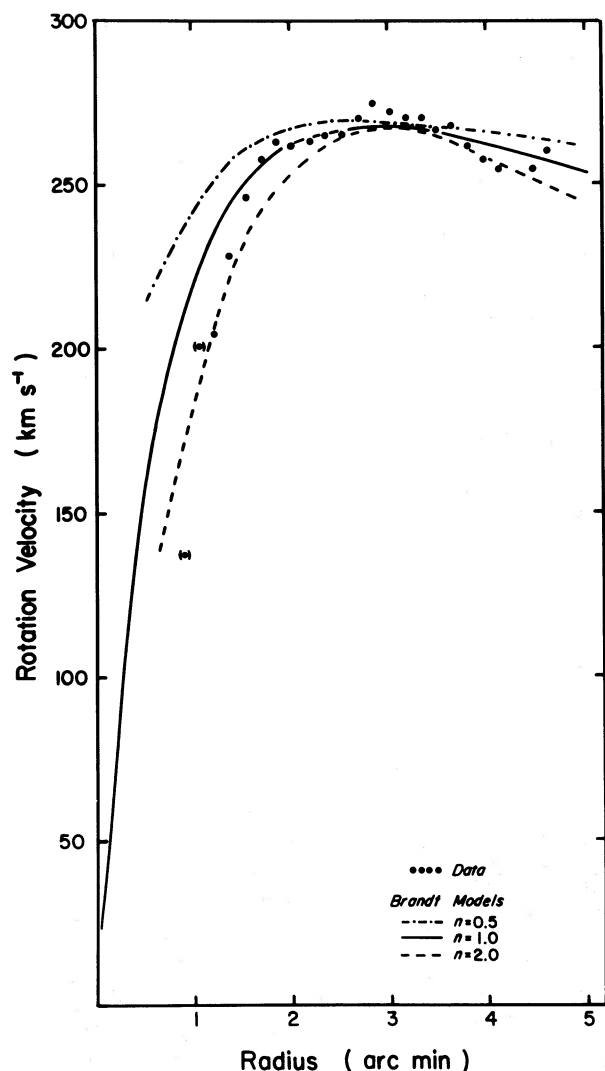


FIG. 3.—Angle-averaged rotation velocities are compared with three Brandt models (Table 3), for which only the shape parameter, n , has been changed. Data points of low certainty are displayed between brackets.

luminosity ratio of the galaxy is, at most, 16, and is more probably one-half that value.

As the rotation curve shown in Figure 3 is quite flat over most of the disk, and since this is usually interpreted to mean that a substantial amount of material lies beyond the last observed point, it is of great interest to calculate the mass within 19.7 kpc (4.7) of the center. Owing to its simplicity, we have applied a Brandt law (Brandt and Scheer 1965) to the data. We recognize that this analytic function has certain undesirable characteristics with respect to total mass determination. However, studies of NGC 5236 and NGC 6503 by de Vaucouleurs and co-workers (preprints), and of IC 1727 and NGC 672 (Combes *et al.* 1980), show that contained masses calculated using different mass functions typically agree to within factors of 2 or 3. A reasonable fit to our data

is given by the parameters in Table 3 where the rotation law is

$$V_{\text{rot}}(R) = \frac{V_{\text{max}} R/R_{\text{max}}}{[\frac{1}{3} + \frac{2}{3}(R/R_{\text{max}})^n]^{3/2n}} \quad (3)$$

As this is an *ad hoc* analytic function, representing a one-component mass model, it is not surprising that the "solution" as shown in Figure 3 does not fit the observations from the inner and outer regions equally well. That is, there is significant uncertainty in the shape parameter, n . However, inasmuch as the inner velocities are not known well, added complexities are not warranted at this time. In any event, adding a central bulge, for example, is unlikely to increase the contained mass by more than 10–15% (Brandt and Scheer 1969). The mass contained within a cylinder of radius 19.7 kpc is $2.9 \times 10^{11} M_{\odot}$, but this reflects a contribution from homoeoids that lie beyond our last observation. The mass of homoeoids only interior to a radius of 19.7 kpc is $2.3 \times 10^{11} M_{\odot}$. Both of these values have been increased by 20% to allow for a disk of finite thickness. These values are similar to the indicative total mass listed in Table 2, where, following Shostak (1978), we used a statistically acceptable Brandt function which is considerably different from the one found best to fit the data shown in Figure 3. In an alternative analysis Casertano and Shostak (1980) find that an accurate estimate of the disk mass within the photometric diameter may be calculated from

$$M_{\text{opt}} = 5.0 \times 10^3 \times \Delta V_0^2 D(0) \Delta M_{\odot},$$

where ΔV_0 and $D(0)$ are given in Table 2 and the distance is $\Delta = 14.2$ Mpc. This formulation gives a mass of $1.6 \times 10^{11} M_{\odot}$ within a radius of 14.3 kpc. As the rotation curve is essentially flat in this region, we would expect this mass to scale up to $2.2 \times 10^{11} M_{\odot}$ at a radial distance of 19.7 kpc. This is very close to the mass calculated from the rotation curve for interior homoeoids only and the congruence is *extremely* gratifying. The imprecision in the Brandt parameters listed in Table 3, particularly n , implies an uncertainty of at most 50% in the contained masses. Thus, employing the larger estimate, the mass within 19.7 kpc of the center is not more than $4.3 \times 10^{11} M_{\odot}$ and must certainly be greater than $1.6 \times 10^{11} M_{\odot}$. However, we believe the most accurate estimate is $2.3 \times 10^{11} M_{\odot}$.

IV. DISCUSSION AND CONCLUSIONS

The mass estimates drawn in the preceding section can be summarized as follows:

1. Our derived mass contained within 59 kpc of the center of NGC 3992 cannot reasonably exceed $4 \times 10^{11} M_{\odot}$, with a mass-luminosity ratio of less than 16.
2. The mass contained within 20 kpc of the center of NGC 3992 has a value close to $2.3 \times 10^{11} M_{\odot}$ and certainly lies within the range $(1.6\text{--}4.3) \times 10^{11} M_{\odot}$.

Accordingly, we conclude that there is little latitude for a massive halo to be associated with this galaxy. A linear increase of halo mass with radial distance from

the center, such as would be inferred from a flat rotation curve, cannot occur unless we adopt the lowest possible Brandt mass for the system (mass contained within 20 kpc) and the largest allowable dynamical mass as derived from the satellites. We consider the latter possibility unlikely because the smallest q value is associated with the satellite having the greatest projected distance from the primary. Also if the rms orbital eccentricity is as large as 0.7, the perigalactic distances of the satellites are well within the optical disk of NGC 3992. There is no evidence that such strong interactions have taken place. This would argue that the orbital eccentricities cannot be much more than ~ 0.3 , if perigalacticon is to be greater than 20 kpc. Hence, the dynamical mass estimates are, if anything, overestimates (by as much as a factor of ~ 2 if the orbits are circular). While the possibility cannot be ruled out absolutely, it would seem that NGC 3992 does not possess a $10^{12} M_{\odot}$ halo, such as those found by Bahcall and Tremaine (1981) for M31 and M101. Van den Bergh (1981) has recalculated the mass within 100 kpc of M31 and finds $(7.5 \pm 3.9) \times 10^{11} M_{\odot}$. It may be significant that NGC 3992 is a strongly barred system and that a halo potential would inhibit bar formation (see Bardeen [1975] for references on this subject). Of course, this leaves open the question of why the rotation curve of the system is flat.

These arguments can be inverted. A referee has pointed out that if we assume a massive halo behaving like an isothermal sphere, then, at large radii, $V_{\text{rot}} = \text{const.}$ and $\rho_{\text{halo}} \propto r^{-2}$. In this regime, it can be shown (Gott 1977) that the halo velocity dispersion $\sigma_H = 2^{-1/2} V_{\text{rot}}$. If the satellite galaxies are large clumps of matter moving

within the halo potential, one would expect their velocity dispersions to be $\sim 175 \text{ km s}^{-1}$. The observed values are 60, 54, and 16 km s^{-1} . A simple χ test for 3 degrees of freedom indicates a rather small probability of $\sim 3\%$ that an extended heavy halo model would exhibit velocity differences as small as those observed. Although this argument is model dependent, it has the virtue of implicitly including all inclination effects on the separations and velocities.

An alternative interpretation of our data is that the "satellites" constitute a small, loosely bound dynamical system, and that NGC 3992 is an interloper, having a nearly coincident systemic velocity with those of the "satellites." If we allow no correction for projection effects (i.e., adopt the extreme assumptions that the actual separations equal the projected separations, and that the actual δV_0 values equal the radial velocity differences), the total energy of the satellite system is marginally positive, $E \approx 0.9 \times 10^{54}$ ergs. Therefore, we consider this interpretation to be unlikely because when allowance is made for projection effects (particularly in the velocity vectors), the total energy of the system rapidly becomes even more positive. In the absence of NGC 3992 the "satellite system" clearly would be unstable.

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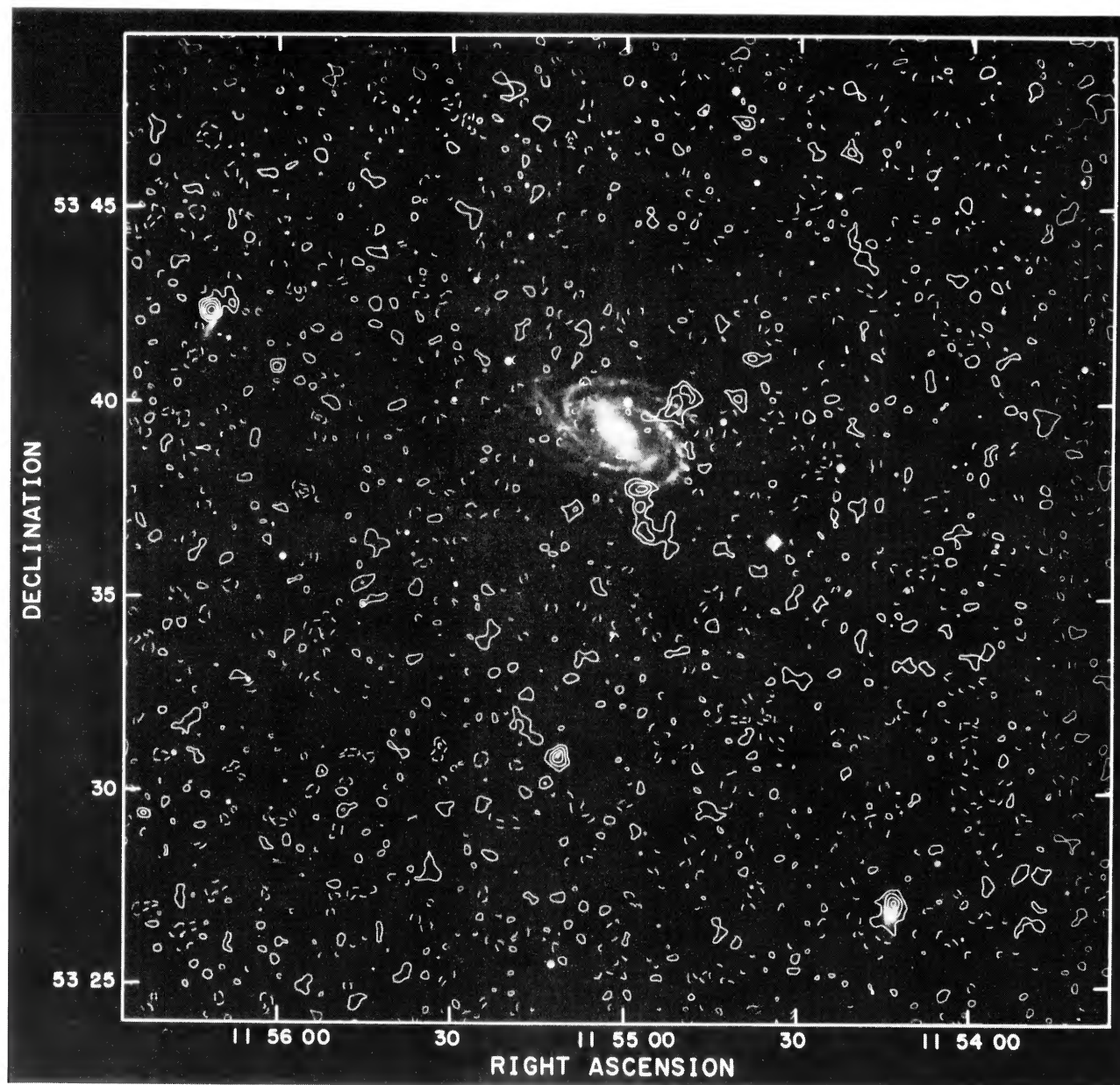


FIG. 1.—H I emission from the field surrounding NGC 3992. The velocity of the gas is 1136 km s^{-1} with respect to the Sun. The first contour, and the contour interval, is 2.5 mJy per beam solid angle. Negative contours are dashed. The rms sensitivity of the survey is 1.5 mJy per beam solid angle. The angular resolution of the survey is $\sim 19''$.

GOTTESMAN AND HUNTER (see page 65)