

NEUTRAL HYDROGEN IN THE M96 GROUP: EVIDENCE FOR A GIANT INTERGALACTIC RING

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ABSTRACT

Further Arecibo observations of the region around the intergalactic cloud in Leo have uncovered several smaller isolated clouds. Altogether, the H I lies primarily along a 200 kpc diameter ring around the galaxies M105 (E0) and NGC 3384 (SB0). The radial velocities around the ring follow a Keplerian orbit pattern with a period of 4×10^9 yr.

Subject heading: galaxies: intergalactic medium

I. INTRODUCTION

Three additional intergalactic clouds have been found during new observations near the recently discovered H I feature in the M96 group (Schneider *et al.* 1983, hereafter Paper I). These new data provide a larger framework for interpreting the H I dynamics and understanding its origin.

Surprisingly the distribution and radial velocities of the gas follow a simple pattern—as if the intergalactic gas is orbiting two of the group's galaxies in a ring. The period of the orbit (and seemingly the minimum age for the feature) is 4×10^9 yr. The orbit model indicates a mass-to-light ratio of about 25 for the central galaxies. Several scenarios for the gas's origin are considered; it appears unlikely that the ring was produced in a gas-sweeping collision. The clouds are probably stable against tidal disruption, requiring a total ring mass of order 10 times the amount observed in H I.

II. DETECTION OF ADDITIONAL H I CLOUDS

In this *Letter*, the results of a search for additional intergalactic H I are presented. Detailed observations of the intergalactic gas and surrounding galaxies will be presented later.

The search for H I was made using the Arecibo 21 cm dual-circular polarization feed.¹ The data taking and reduction procedures were like those described in Paper I, except that overlapping 5 MHz spectra were used, covering velocities from 200 to 2000 km s⁻¹ with a resolution of 8 km s⁻¹ and about a 2.5 mJy noise level after Hanning smoothing. The observing grid from Paper I was extended, and a number of points reobserved. The 21 cm flux contours based on the combined results are displayed in Figure 1a (Plate L1).

Three small clouds were found ranging up to a degree north of the main cloud complex. None of the clouds is associated with optical emission on the Palomar Sky Survey plates.

To facilitate this discussion the four subcondensations already evident in the main cloud complex, together with the

new features, have been labeled as clouds I–VII in Figure 1a. In Table 1 average parameters of each cloud (col. [1]) are presented, adopting a distance of 10 Mpc for the clouds and GWA group (see Paper I). Half-peak intensity dimensions of the clouds (col. [2]) are uncertain since the half-power beam width corresponds to almost 10 kpc. Flux-weighted heliocentric velocities, half-peak velocity widths, H I column densities, and H I masses are given in columns (3)–(6). Central densities (col. [7]) and virial masses (col. [8]) are based on a three-dimensional Gaussian distribution with the depth taken as the smaller of the projected dimensions. Only the local velocity dispersion was used to estimate the virial mass since the velocity gradient within each cloud probably results from orbital motion.

III. VELOCITY STRUCTURE OF THE INTERGALACTIC GAS

After the original observations, Briggs (1983) suggested that the velocity gradient across the main cloud complex might reflect a trajectory about the galaxies M105 and NGC 3384; however, the data were then inadequate for a detailed examination of this possibility. With the new clouds, it is now possible to test a simple orbit model.

An ellipse was fitted through clouds II–VII (see Fig. 1b), and the radial velocities along the ellipse were modeled by a nonlinear least squares algorithm, which solved for the orbital parameters using the radial velocities alone. For comparison, a purely geometric orbit model was constructed using the fitted ellipse and assuming the center of mass lay at the luminosity-weighted centroid of M105 and NGC 3384. (Throughout this *Letter*, extinction-corrected luminosities of the galaxies are drawn from the revised Shapley-Ames catalog [Sandage and Tammann 1981], and velocities from the CfA survey [Huchra *et al.* 1983].) In Table 2 the orbital parameters and formal errors of the kinematic and geometric models are presented along with several derived quantities. In Figure 2, the models of the radial velocities are displayed.

The agreement between the models is remarkable. The kinematic model independently predicts a position of the orbital focus lying only 15 ± 7 kpc from the centroid of M105

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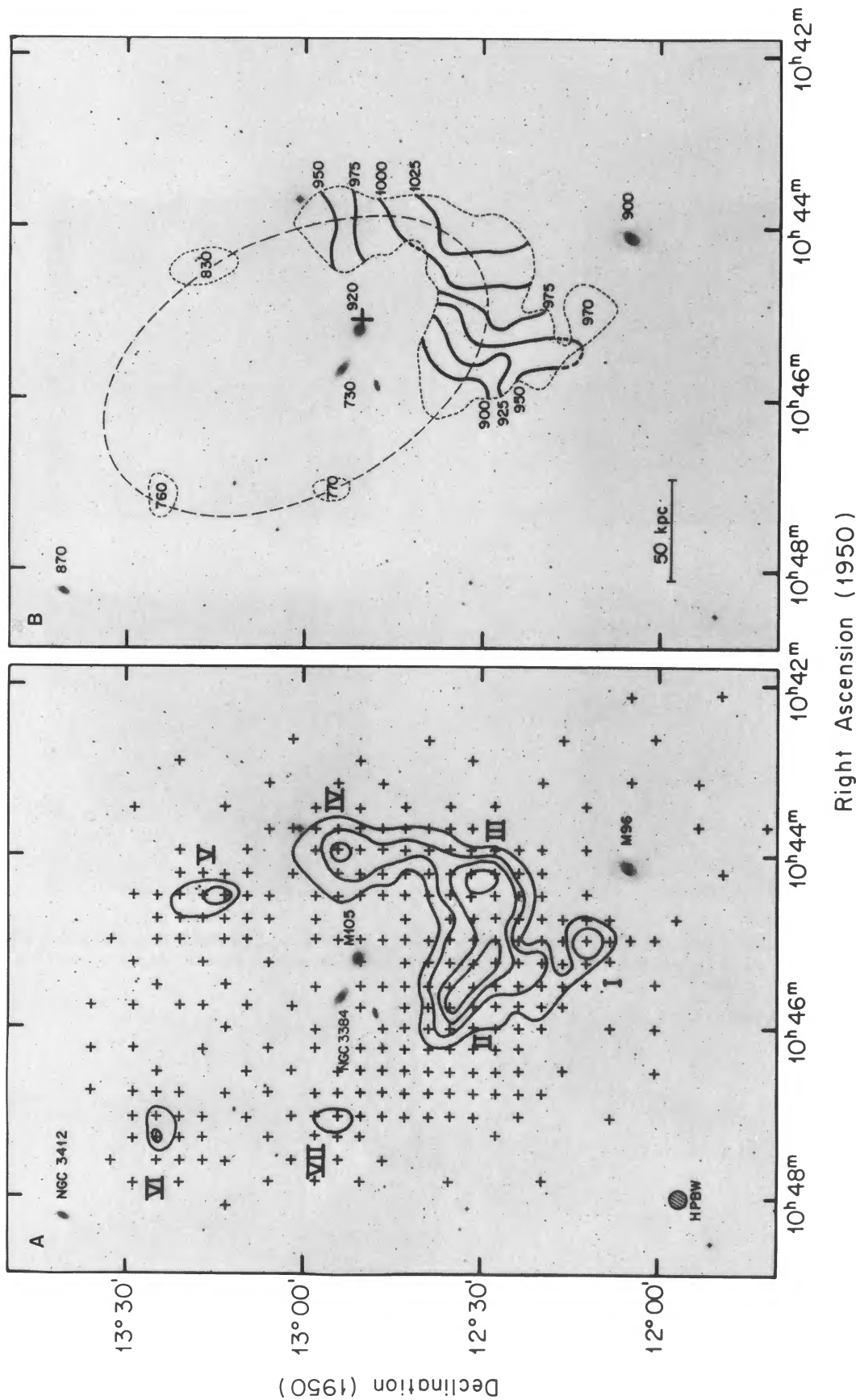


FIG. 1.—(a) Distribution of the intergalactic neutral hydrogen. Integrated flux contour levels are at $\int T_B dv = 5, 10, 20$, and 40 K km s^{-1} . The points observed are marked with crosses. The local peaks in the H I intensity are labeled as clouds I–VII. The half-power beamwidth is shown in the bottom left corner. (b) Heliocentric velocity contours in the main cloud complex, and velocities of the individual clouds and galaxies. An ellipse fit through clouds II–VII is shown, and the position of the focus predicted from the radial velocity pattern is marked by a cross. The 50 kpc scale assumes a distance to the group of 10 Mpc. (The figures are superposed on blue plate photographs from the ©1960 National Geographic Society—Palomar Sky Survey, reproduced by permission of the California Institute of Technology.) SCHNEIDER (see page L33)

TABLE 1
CLOUD PARAMETERS

Cloud (1)	Dimensions (kpc) (2)	V_{hel} (km s^{-1}) (3)	ΔV_{50} (km s^{-1}) (4)	N_{max} (10^{19} cm^{-2}) (5)	$M_{\text{H I}}$ ($10^7 M_{\odot}$) (6)	n_0 (10^{-3} cm^{-3}) (7)	$M_{\text{c}}/M_{\text{H I}}$ (8)
I	17×18	970	20	2.8	7.8	0.5	17
II	15×48	940	35–60	8.6	70.	1.7	14
III	25×31	1020	30–45	8.7	55.	1.1	13
IV	18×42	970	45	3.7	32.	0.6	29
V	18×34	830	25	1.8	6.8	0.3	39
VI	16×23	760	25	1.6	5.3	0.3	40
VII	13×20	770	30	1.2	3.4	0.3	75

NOTE.— Spin temperature corrections to the nominal H I densities and masses are probably less than 4 (see Watson and Deguchi 1984).

TABLE 2
PARAMETERS OF ORBIT MODELS

Parameter	Kinematic	Geometric
Eccentricity	0.41 ± 0.03	0.29 ± 0.05
PA of ascending node (deg)	219 ± 3	210 ± 7
PA of periape (deg)	218 ± 6	203 ± 10
Inclination (deg)	47 ± 5^a	50 ± 5
Heliocentric velocity of focus (km s^{-1})	829 ± 3	841 ± 13
Orbital velocity at periape (km s^{-1})	256 ± 19	
Semi-major axis (kpc)	104 ± 7	
Mass ($M_{\odot}$)	$6.4 \pm 1.1 \times 10^{11}$	
Period (yr)	$3.9 \pm 0.3 \times 10^9$	

^a Based on observed vs. predicted eccentricities only.

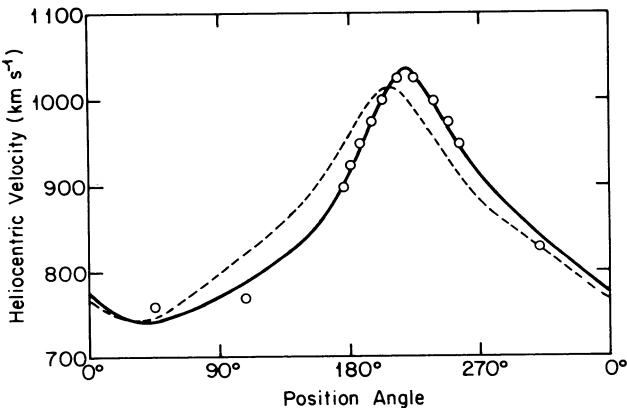


FIG. 2.— Keplerian models of the radial velocities around the intergalactic ring. The solid line shows the kinematic fit to the observed velocities, and the dashed line shows the pattern predicted by the geometry of the fitted ellipse in relation to the central galaxies. Position angles are referenced to the center of the ellipse shown in Fig. 1b. The geometric model suffers mainly from the weakly determined position angle of the line of nodes.

and NGC 3384 (see Fig. 1b) with an insignificant difference ($12 \pm 13 \text{ km s}^{-1}$) from the centroid's radial velocity. The central mass corresponds to a mass-to-light ratio of ~ 25 if the mass is entirely associated with M105 and NGC 3384. This is a modest value of M/L compared to most velocity-dispersion estimates for groups of galaxies.

That this naive description should fit the data so well was unexpected since two details appeared to defy a simple orbit

model. First, the cloud gas is clearly interacting with M96 as indicated by the extension (cloud I) pointing toward it. Second, the velocities within cloud III continue rising away from M105 and NGC 3384, contrary to a Keplerian decline. It is possible that these two problems are related, with the outer edge of the cloud falling in M96's sphere of influence. Alternatively, the rising velocities might be caused by the internal dynamics of cloud III or by an extended distribution of dark matter. In any case, the basic parameters of the derived orbit are probably good first-order approximations.

The predicted orbital period of $4 \times 10^9 \text{ yr}$ is longer than the crossing time for the group, raising the question of the ring's stability. Several coincidences may resolve this problem and shed light on the whole group's dynamics. De Vaucouleurs (1975) noted that the group is centered on a dense core consisting of the galaxies M95, M96, M105, NGC 3377, NGC 3377A, NGC 3384, and NGC 3412. This core region has dimensions of about 1.5 by 3° and a position angle of about 35° . The intergalactic ring lies near the center of this region with similar aspect ratio and orientation. The core galaxies have a luminosity-weighted mean velocity of 835 km s^{-1} and display a slight trend on average from higher velocities in the southwest to lower in the northeast, similar to the H I. Thus, it is possible that the whole group is rotating in the same sense as the ring, making disruptive collisions less likely.

These circumstances suggest that the intergalactic gas could be a primordial remnant of the group's formation, gas which was perhaps unable to collapse because of its high angular momentum or because of tidal stirring by the surrounding galaxies.

Such a situation might also provide the conditions necessary for creating a ring structure by tidal encounters. A galaxy in the group (M96?) may have undergone repeated tidal encounters during its orbit, the fragments of which have been distributed along its orbital path. Alternatively, if NGC 3384 had been surrounded originally by a nearby ring of gas like some S0's (see van Woerden, van Driel, and Schwarz 1983), tidal deformation by a galaxy (M105?) orbiting in the same sense as the gas might "pump up" the ring. Coincidentally, NGC 3384 has a position angle of 52° and an inclination of 64° (Barbon, Capaccioli, and Tarenghi 1975) so that, up to the ambiguity in the spatial orientation, the spin axes may differ by less than 20° . However, the evidence for tidal interaction between NGC 3384 and M105 is uncertain (Nieto and Vidal 1984),

and the lack of stars observed in the intergalactic gas may prove problematic for any tidal scenario (Skrutskie, Shure, and Beckwith 1984).

Rood and Williams (1984) have proposed instead that NGC 3384 was once a spiral galaxy which has been stripped of its gas in a collision with M96, leaving a cloud of gas that is expanding freely as a ring because of its angular momentum. Extended to the new observations, this explanation seems appealing, for it predicts a ring shape as well as the agreement with the orientation of NGC 3384. This model is inconsistent, though, with other details of the observations. At the ring's present size, the gas would be flowing almost radially away from the impact point. To account for the observed pattern of velocities, the plane of outflow would have to be nearly perpendicular to the plane of NGC 3384, and the gas distribution *more* eccentric than its sky projection. The agreement with the orientation of NGC 3384 is then entirely fortuitous and the angular momentum expected from NGC 3384 somehow suppressed (assuming of course that NGC 3384 is an oblate spheroid). The presence of only NGC 3384 near the center of the ring would also be unexpected since the motion of the colliders should have carried them to opposed positions about the collision center.

IV. MASSES OF THE CLOUDS

The lifetime of the individual clouds in the ring sets constraints on their masses. Even in a tidal scenario, the distribution of gas at points all around the ring requires that at least some of the clouds have persisted for a full orbit. Differential rotation could not have spread out the matter in less than a single orbit given that the orbital radii of clouds diametrically opposed about NGC 3384 and M105 do not differ by more than a factor of ~ 1.5 .

It does appear that some of the clouds have been slightly stretched by differential rotation. The most clearly elongated clouds and the extension toward M96 all present angles relative to the orbital ellipse that are consistent with differential smearing in a clockwise orbit. However, the isolated clouds (V–VII) are smeared much less than would be expected for their apparent radial extent. If these clouds were unbound, they should stretch over 60° of the orbit after one period. If the clouds are stable against tidal disruption, they must have masses comparable to the virial masses listed in Table 1.

Since the gas would be almost entirely ionized above 3000 K, and the velocity gradients within the beamwidth of the telescope are not so large, most of the velocity width observed

in each cloud must result from local bulk turbulence. An ambient medium might pressure confine the subcomponents within the clouds, but it could not prevent differential smearing. For reasonable parameters of a surrounding hot gas in pressure balance with the clouds, evaporation does not appear to set an important limit on the clouds' lifetimes (see Cowie and McKee 1977). Instead, it appears that ionization balance with the hot electrons in an ambient gas might require a substantial H II shield, possibly massive enough to gravitationally bind the clouds.

The simplest model to account for the clumpy nature of the ring is to require local gravitational enhancements in each cloud having nearly the virial masses suggested by the internal velocity dispersions of the clouds.

V. DISCUSSION

Most searches for intergalactic clouds have concentrated unsuccessfully in groups of late-type galaxies. It is perhaps significant then that the M96 group is the nearest of de Vaucouleurs's groups with a preponderance of early-type galaxies. Spectroscopic studies of the internal dynamics of these galaxies, particularly NGC 3384, might help explain their relation to the ring.

The discovery of more clouds in continuation of a conjectured orbital ellipse presents a unique probe of the distribution of mass at large in a group of galaxies. An initial examination indicates that the dark matter is concentrated near the galaxies since a simple Keplerian orbit model is capable of reproducing the pattern of radial velocities around the ring, although some inconsistencies remain that may be explained by non-Keplerian motion. However, given the ring's apparent eccentricity, the gas's orbit should not be closed for the non-inverse square force law of an extended halo of dark matter (or of the modified Newtonian dynamics proposed by Milgrom 1983); but of course, there is no guarantee that the gas would be distributed throughout a complex orbit pattern. More extensive and more sensitive H I observations are clearly needed.

The new observations suggest that the intergalactic gas in the M96 group is of considerable age, although a tidal origin cannot be ruled out. It appears that only a measurement of the clouds' metallicity can finally determine whether the intergalactic gas is primordial or tidal and reveal its relation to the dynamics and evolution of the surrounding galaxies.

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