DISTRIBUTION AND MOTIONS OF ATOMIC HYDROGEN IN LENTICULAR GALAXIES

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ABSTRACT

We report the results of HI observations of eleven gas-rich SO/SOa galaxies with the Westerbork Synthesis Telescope. The majority of these galaxies have most of their hydrogen outside the optical body, in annular configurations with diameters ~2 times the optical. These outer gas rings are often clumped, incomplete, and in approximately circular motion. They may represent the remnants of primordial, often warped, gas disks; or they may have formed from gas (or dwarf galaxies) accreted recently. Optical spectra could discriminate between these possibilities.

A few objects have filled gas disks, and several have inner HI rings with radii ~0.4 × optical. Two objects have peculiar distributions suggesting, respectively, tidal effects and stripping. However, stripping by intergalactic gas appears not to be a major current process.

1. INTRODUCTION

The gas content of lenticular (or, equivalently, SO) galaxies plays a key role in the problem of their origin and evolution.

Faber and Gallagher (1976) estimate that a galaxy of blue luminosity L_B should, through mass loss from evolving stars, in a Hubble time produce an amount of interstellar gas, M_g, given by $M_g/M_\odot \sim 0.1\ L_B/L_\odot$. Such amounts should be readily detectable, but are rarely observed in SO galaxies. Faber and Gallagher consider several ways to remove the gas. Star formation would probably make the SO's bluer than they are observed to be. Stripping by collisions with other galaxies or with intergalactic gas might work in clusters, but not for field SO's. Faber and Gallagher conclude that hot, supernova-driven galactic winds are probably responsible for the lack of gas in SO's.

Larson, Tinsley and Caldwell (1980) calculate that star formation will exhaust the disk gas in most spiral galaxies in a fraction of the Hubble time. They suggest that spirals are replenished from gas-rich envelopes consisting of tidal debris, dwarf companions and/or remnants of primordial gas; and that SO's were formed from disk galaxies which early lost their envelopes and then consumed their gas by star formation. Larson et al. consider that gas produced later by evolving stars may be removed by intergalactic gas, by galactic winds, or by short bursts of star formation.

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Thus, the absence of gas traditionally assumed in SO galaxies may be theoretically understood. But what is the observational situation?

Since 1975, major surveys of the HI content of SO and SO/a galaxies have been carried out at Arecibo, Green Bank and Parkes. Some 200 objects have been observed, and about 40-50 of these detected. The M_{HI}/L_B values measured range between <0.001 and 0.6. Clearly, the gas content of SO and SO/a galaxies varies over a wide range. This fact suggests that the HI component in these galaxies may be a transient phenomenon, and that we see them in different stages of evolution.

In an attempt to understand the origin and evolution of the gas in lenticular galaxies, we have measured the HI distribution and velocity field in a large number of such galaxies with the Westerbork Synthesis Radio Telescope. The present paper summarizes the current results of this program, and draws some tentative conclusions.

2. WESTERBORK OBSERVATIONS

For our Westerbork program, we selected galaxies of morphological type SO or SO/a (as listed in the Second Reference Catalogue, RC2), having a good HI detection in the recent surveys, positive declination, and sufficient angular size. Our sample spans considerable ranges in M_{HI}/L_B and in luminosity. Table 1 lists 11 objects for which maps are now available; it includes a few objects observed by colleagues at Groningen, who kindly made their results available for the present discussion. Several more objects have been observed, and the program continues. The Revised Shapley Ames (RSA) types listed show that most of our objects are genuine SO's or SO/a's.

The observations have ~40 km/s velocity resolution; the angular resolution is 0!4 in α and 0!4/sin δ in δ for most objects.

3. THE HYDROGEN DISTRIBUTIONS AND MOTIONS

In this section, we first describe the results obtained in two typical cases: NGC 4203 and 4262. Next we summarize and discuss the gas distributions and motions found in our sample of 11 galaxies.

3.1. NGC 4203 and 4262

NGC 4203 is a pure SO galaxy of optical diameter D_{25} = 3!6 and inclination i ~ 30°. The hydrogen in this galaxy has been mapped at Arecibo with 3' resolution by Burstein and Krumm (1981). We find (Fig. 1) most of the gas to lie outside the optical body, in an annular configuration of 6!5 diameter, i.e. almost twice the optical. This outer HI ring is incomplete and strongly clumped. If its true shape is roughly circular, it has an inclination of ~60° to the plane of the sky, and of 30° or 90° to the stellar disk. We also observe an inner ring, of dia-

Figure 1. Hydrogen distribu-
tions (left) and velocity
fields (right) for two gala-
xies. Column density contour
values are 1.0, 2.0, 3.0 ×
10^{20} atoms/cm^2 for NGC 4203;
and 1.4, 2.8, .. 7.0 × 10^{20}
atoms/cm^2 for NGC 4262. Velo-
cities (in km/s) are heliocen-
tric. The dashed ellipses are
25 mag/arcsec^2 isophotes from
RC2; the shaded ellipses show
the angular resolution of the
HI observations. Linear scales
are for distances based on
H_O = 100 km s^{-1} Mpc^{-1}.

The HI distributions are
dominated by incomplete,
clumpy, tilted outer-ring
configurations. The velocity
fields indicate that these
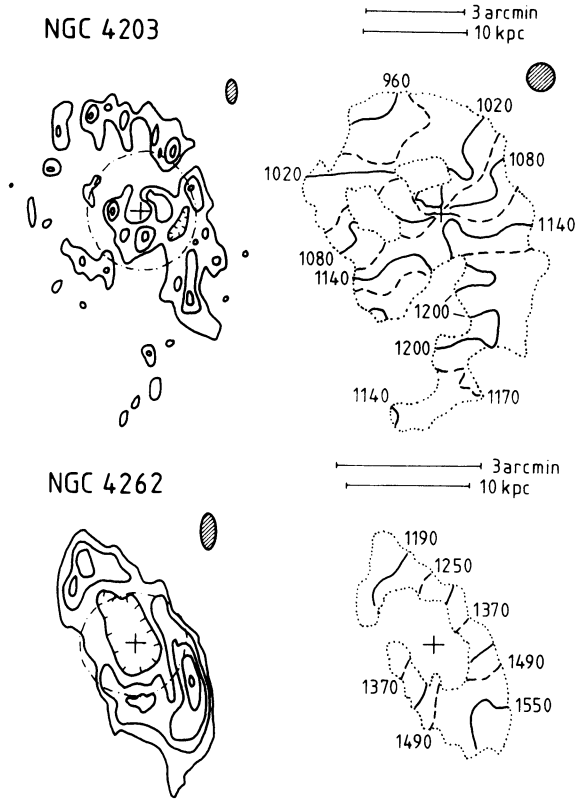rings are in approximately
circular rotation.

NGC 4203

NGC 4262

TABLE 1
Structural and dynamical properties of HI in lenticular galaxies

(1) Name NGC	(2) Morphol. type (RC2)	(RSA)	(3) Features in HI distribution c r , D_r^i, χ (d) R, D_R^i , χ T	(4) Notes	(5) hR$_R$ kpc	(6) V$_{rot}$ km/s	(7) hP$_R$ 10^9yr	(8) hM$_R$ 10^9M$_\odot$	(9) M$_R$/hL$_B$ M$_\odot$/L$_\odot$
1023	S B O-	SBO 1	R,2.5 , < T	2 vel. systems	25	150	1.1	110	8
2273	SABrsO:		d R,0.8 , <		8	210	0.2	80	7:
2787	S Br O+	SBOa	R,2.5:,60°						
3900	SA r O+	S a(r)	r$_0$,0.4, < d	*	11	220	0.3	120	14
3941	S Bs O+	SBOa1-2	r ,0.4, < R,1.6 , <		8	160	0.3	50	9
3998	SA r O?	S O 1	r? R?0.7:,70°	**	4:	280	0.1	70:	12:
4203	SAB O-	S O 2	r ,0.4, < (d) R,1.8 ,30°		11	150	0.4	60	10
4262	S Bs O-?	SBO 2-3	R,1.7 ,40°	Virgo Cluster	7	240	0.2	90	27
4694	S B Op	Amorph	c T	Virgo Cluster					
5084	S O/	S O 1	R,2.5 , <		27	310	0.5	600	60
7013	SA r Oa		r$_0$,0.4,25°: d R,0.85, <	***	6	170	0.2	40	7

Key to Table 1
(2)   Morphological types, from Second Reference Catalogue (RC2) and Revised Shapley Ames Catalog (RSA)
(3)   Features in HI distribution: c = concentration at centre; r = inner ring; r$_0$ = r coinciding with
        optical inner ring; d,(d) = filled, resp. partly filled gas disk; R = outer ring; T = tail. D_r^i,
        D_R^i give ring diameters relative to D$_{25}$ (from RC2); χ = inclination of ring (assumed circular)
        relative to optical disk; < means χ is small.
(4) * NGC 3900: Data in columns (5)-(9) given for edge of HI disk.
    ** NGC 3998: Diameter and category of HI ring uncertain.
   *** NGC 7013: Inner ring tilted or motions non-circular.
(5)-(7) Linear radius R$_R$, rotation speeed V$_{rot}$, and period P$_R$ of outer HI ring.
(8),(9) Total mass M$_R$ within outer ring (assuming spherical distribution), and ratio to blue luminosity L$_B$.

meter 0.4 D_{25} and negligible tilt relative to the disk. A smoothed map
shows weak disk emission between both rings. The velocity field is some-
what irregular, but circular motions in a warped disk with a flat rota-
tion curve give a reasonable fit.

NGC 4262 is an almost face-on (i < 30°), barred S0 galaxy of 2.'2
diameter, 3° NW of the centre of the Virgo Cluster. Its hydrogen (Fig.
1) lies in an outer ring of 3.'7 diameter (i.e. 1.7 × optical) and 60°
inclination (if circular), hence tilted >30° relative to the disk. The
ring is fairly complete, but quite uneven in brightness. The velocity
field bears the signature of solid-body rotation, indicating a circular
ring in circular motion.

3.2. A summary for 11 galaxies

Table 1 summarizes our results for 11 galaxies. Among these, 8 have
most of their hydrogen in outer-ring configurations (R), with diameters
between 0.8 and 2.5 times the optical (D_{25}). In general, these rings are
roughly concentric with the optical disk; however, if circular in shape,
several are strongly inclined to the disk. The density distributions in
these rings are quite uneven; some are strongly clumped, and often parts
of the ring are not detected. The velocities measured in the rings
closely follow the pattern of circular rotation; in NGC 1023 two velo-
city systems are observed. In section 4 we discuss the rotation speeds
and periods, and the galaxy masses derived.

Four galaxies have inner HI rings (r) of diameters about 0.4 times
the optical disk. Except in NGC 3900, these inner rings combine with
outer HI rings. In NGC 3900 and 7013, they approximately coincide with
optical (probably stellar) inner-ring features. In NGC 7013 the velocity
field indicates that the inner HI ring is tilted relative to the disk,
or that it possesses non-circular motions.

HI distribution and motions in NGC 3998 indicate a ring observed
edge-on and highly inclined to the optical body (cf. Knapp, this sympo-
sium). The ring diameter is uncertain because of the edge-on situation.

In four galaxies we observe a disk of hydrogen, in addition to an
inner and/or outer ring. In NGC 4203 we find a faint, extended disk. The
HI disks in NGC 2273, 3900 and 7013 are about as large as the optical
disks; these 3 galaxies, however, may be early-type spirals.

Two galaxies in Table 1 have exceptional HI distributions. NGC 1023
(Sancisi et al., in preparation) shows an incomplete outer ring in
circular motion, an anomalous velocity system, and a bright HI tail. The
tail and the anomalous-velocity system may be due to tidal action of NGC
1023 on a nearby, smaller late-type galaxy. NGC 4694 has a narrow,
clumpy HI tail and an unresolved central condensation of gas. This
unique distribution and the galaxy's location in the Virgo Cluster (5°
SE of the centre) suggest stripping by intergalactic ram pressure as a
possible cause.

4. ROTATION SPEEDS AND PERIODS; MASSES AND M/L RATIOS

The observed outer gas rings allow us to derive some dynamical properties of gas-rich lenticular galaxies. The results (Table 1) are given for distances based on a Hubble constant $H_o = 100$ h km s^{-1} Mpc^{-1}.

The outer HI rings have radii R_R ranging from 6 to 27 h^{-1} kpc. Assuming circular ring shapes to derive inclinations, we find rotation velocities V_{rot} between ~150 and ~300 km/s. The present sample shows no Tully-Fisher relation between rotation velocity and luminosity, a finding similar to that of Dressler and Sandage (1982, and this symposium) from optical rotation curves for another sample of SO's. The rotation periods of the outer HI rings range between 2 and 10 h^{-1} 10^8 years.

Assuming spherical mass distributions, we derive total masses inside the outer HI rings, $M_R = V_{rot}^2 R_R/G$, ranging from 0.4 to 6 h^{-1} 10^{11} solar masses. The total-mass-to-blue-light ratios cluster around 10h; two values are much higher. We find no correlation between M_R/L_B and relative ring diameter, D_R/D_{25}.

5. ORIGIN AND EVOLUTION OF THE GASEOUS COMPONENT

In this section we draw some tentative conclusions from the observational results summarized in section 3 and Table 1.

1) Our major finding is that in many gas-rich lenticulars most of the hydrogen is located in the outer parts, or even outside, of the luminous body. This strongly suggests that stripping by intergalactic ram pressure is not a major current process in SO galaxies. For such stripping should primarily remove the gas in the outer, rather than the inner, parts. The only likely stripper in our sample is NGC 4694, a galaxy in the Virgo Cluster. However, the other Virgo member, NGC 4262, has all of its gas in a well-formed outer ring structure!

2) The frequent outer rings might well be interpreted as a stage in the process of gas removal by galactic winds. However, it is unclear that such winds would produce the observed uneven distributions in the outer HI rings. Also, the circular motions observed may be inconsistent with angular momentum conservation in an outward gas flow (although this argument may be invalid in non-axisymmetric cases).

3) Another possibility to be considered is that of accretion of intergalactic gas clouds, tidal debris or dwarf companions (cf. Silk and Norman, 1979) by a formerly gas-poor lenticular galaxy. The uneven structure of the outer rings may suggest dwarf capture. The close-to-circular motions suggest that capture occurred a few periods, that is: about 10^9 years, ago. The inner HI rings observed in a few cases might be due to earlier accretion, cf. the Spindle galaxy, NGC 2685 (Shane, 1980).

4) Finally the outer rings may represent the remnants of primordial, often warped gas disks, of which the dense inner parts have been used up in star formation, while the tenuous outer parts never gave birth to stars. (For removal of the gas produced later in the inner parts by stellar evolution, a galactic wind may then still be required.) This scenario is partly similar to that of Larson, Tinsley and Caldwell (1980) summarized in section 1. However, most of our gas-rich SO's apparently do have gas-rich envelopes, which somehow may have failed to replenish the inner disks.

These are tentative suggestions, which will have to be analyzed in detail before they can lead to firm conclusions. However, an important observational test appears evident. Comparison of the sense of rotation in the outer gas rings with that in the inner, stellar disks should decide for or against scenario 3). Opposite senses of rotation would require accretion; if the senses always agree, recent accretion of dwarfs or intergalactic gas can probably be ruled out.

Another item for further study is what the gas distributions tell us about the place of SO galaxies in the morphological sequences. For this purpose, we have undertaken a companion program on Sa galaxies, as part of a comparison between lenticulars and spirals. Also, the relationship of the outer HI rings to the phenomenon of optical outer rings requires investigation.

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