THE COLD INTERSTELLAR MEDIUM IN ELLIPTICAL GALAXIES - OBSERVATIONS OF HI AND RADIO CONTINUUM EMISSION

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ABSTRACT. About 10% of nearby elliptical galaxies contain HI, with typical values of M(HI) ~ 5×10^8 $M_\odot$ and M(HI)/L_B ~ 0.03 $M_\odot/L_\odot$. The HI content is unrelated to the stellar content, (unlike the situation in spiral galaxies) suggesting that the HI in early-type galaxies has an external origin and is not produced by mass loss. This conclusion is strengthened by the distribution and kinematics of the HI structures, which lie outside the main optical body of the galaxies, have much larger specific angular momentum than do the stars, and are often highly inclined to the kinematic and distribution axes of the optical bodies.

The HI and stellar kinematics show that the rotation curves of E and SO galaxies are approximately flat from small (a few hundred pc) to large (10-20 kpc) radii, as is the case for spirals. Likewise, large mass-to-light ratios are found for some systems. Comparison with mass models derived from X-ray emission suggests that these may in some cases overestimate the mass.

The presence of HI is shown to enhance the likelihood that an E/SO galaxy has a nuclear radio continuum source, in agreement with models which suggest that the central engine is fuelled by cold gas. Current data suggest that the gas-to-dust ratio for the cold interstellar medium in ellipticals has a value similar to that found in the solar neighborhood.

1. INTRODUCTION

Sensitive data accumulated in the last ten years or so have shown that, after all, elliptical galaxies have an interstellar medium of sorts, observable in almost all of the familiar signatures, i.e. optical line emission from ionized gas, optical line absorption, diffuse X-ray emission, HI emission and absorption, dust absorption at visual wavelengths and diffuse infrared emission from cool dust. This contribution discusses some of the issues raised by these observations which relate to the origin of the cool interstellar medium, i.e. whether its origin is internal or external to the galaxy, how it is

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affected by the environment of the galaxy, how it is related to the nuclear radio sources seen in some ellipticals, and what dynamical information can be found from the observations.

2. THE GLOBAL HI CONTENT OF ELLIPTICAL GALAXIES

About 10% of nearby ellipticals are currently detected in the HI 21 cm line. The observed HI content ranges from a few × 10^5 $M_\odot$ for the Local Group dwarfs NGC185 and NGC205 (Johnson and Gottesman 1983) to a few × 10^9 $M_\odot$ for NGC807 (Dressel, this conference) [H_o = 100 km/sec/Mpc assumed]. Typical values of $M(HI)/L_B$ are ~ 0.03 $M_\odot/L_\odot$, although this quantity shows a very wide variation.

The distribution of $\phi[M(HI)/L_B]$, where $\phi(x)$ is the fraction of galaxies in a sample with a given value of x, can be compared for spiral and elliptical galaxies. For Sc galaxies, for example, ϕ has a well-defined average value and small dispersion (c.f. Figure 1d), reflecting the interrelationships between gas and stars in disk galaxies. The evaluation of ϕ for elliptical galaxies has to take into account the facts that most ellipticals are undetected in the HI line and that the upper limits have similar values to the detections. Methods for estimating ϕ for such data sets are described by Knapp, Turner and Cunniffe (1985), Feigelson and Nelson (1985), and Wardle and Knapp (1986). The resulting distribution, shown in Figure 1a, shows a much wider range of relative HI content than is seen for Scs, suggesting that in Es, the gas and stars are not evolving together. Thus much of the HI seen in Es may have an external origin. The values of $M(HI)/L_B$ in ellipticals range from ~ 3×10^{-3} to 0.3; the predicted fraction of ellipticals containing HI in this range is ~ 45%, in reasonable agreement with the fraction of ellipticals expected to contain dust (Sadler and Gerhard 1985).

In Figure 1 the distributions of $M(HI)/L_B$ in SOs and SO/as are also given. These distributions show that the global HI properties of galaxies have a steady progression from E→SO→SO/a→spiral. The distribution for SO/as is like that for spirals, with a reasonably well-defined mean value (~ 0.04 $M_\odot/L_\odot$). The distribution for SOs, however, resembles that for ellipticals and thus these two types of galaxies are similar to each other and different from spirals. The two types are, indeed, often difficult to tell apart morphologically (e.g. Kent 1985, and much discussion at this conference).

Despite the skimpy statistics, environmental effects on the occurrence of HI can be observed. For example, Wardle and Knapp (1986) show the distance distribution for their sample of E, SO and SO/a galaxies for both HI detections and non-detections. The HI detection rate, and the occurrence of SO/a galaxies, is very much lower in the Virgo cluster than elsewhere.

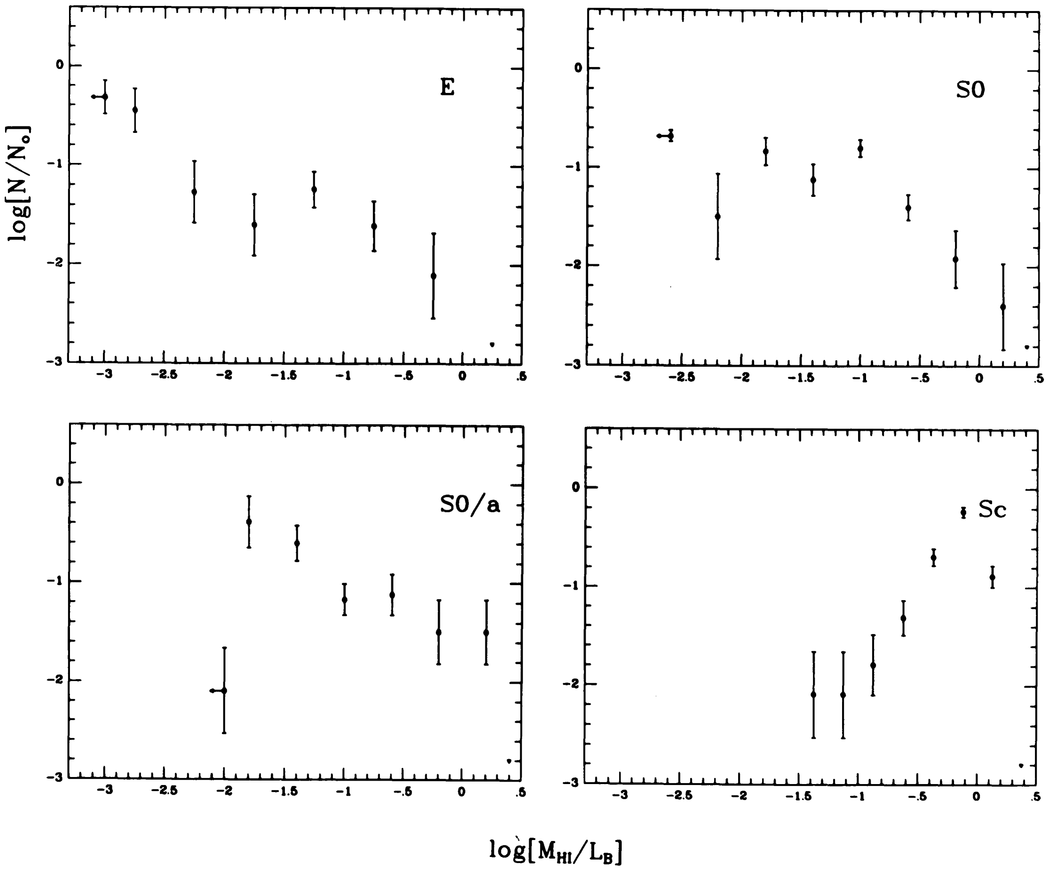

Figure 1. Distribution ϕ [M(HI)/L_B], where ϕ is the fraction of galaxies with a given value of M(HI)/L_B, for (a) E galaxies (upper left) (b) SOs (upper right) (c) SO/as (lower left) and (d) Scs (lower right). The HI observations for the Scs are by Shostak (1978).

3. HI DISTRIBUTION AND KINEMATICS

Several E and SO galaxies contain enough HI that its distribution and kinematics can be mapped using synthesis arrays, i.e. the Westerbork array and the VLA. There is no space in this contribution to describe details of the individual galaxies [some of these are discussed by van Gorkom (this conference) and Dressel (this conference)]. The ensemble of results suggests:

(1) The HI emission is often distributed in large rings lying outside the main body of the galaxy. This is seen, for example, in the elliptical NGC4278 (Raimond et al. 1981 and in preparation) and in the SOs NGC2655 (Shane and Krumm, in preparation) NGC4203 (van Driel et al., in preparation) and NGC5084 (Gottesman and Hawarden 1986).

There is no accompanying stellar disk in these galaxies or other galaxies of this type (c.f. Hawarden et al. 1981).

(2) The HI features are often highly inclined to the stellar galaxy, both structurally and kinematically. Inclinations of > 60° are seen, for example, for the ellipticals NGC4278 (Raimond et al. 1981) NGC1052 (van Gorkom et al. 1986) NGC5128 (van Gorkom, this conference) and NGC5666 (Lake et al. 1986) and for S0s NGC3998 (Knapp et al. 1985) and NGC2787 (Shostak 1986). Exceptions do exist - NGC5084 and NGC807 (Gottesman and Hawarden 1986; Dressel, this conference) have HI structures along the bulge major axis.

(3) The specific angular momentum for the gas is much greater than that of the stars; the gas is usually at larger radii than are the stars and appears to be rotationally supported.

(4) Some of the gas structures in E and S0 galaxies show elongated and warped structures which are reminiscent of tidal tails (e.g. NGC1052, van Gorkom et al. 1986, and NGC1023, Sancisi et al. 1984, where the observations clearly show the interaction between a gassy dwarf and the massive early-type galaxy).

(5) Non-circular motions of the HI are apparent in the inner regions of some Es (e.g. NGC1052, van Gorkom et al. 1986a). In particular, some radio galaxies have HI absorption components which are redshifted with respect to the galaxy's systemic velocity.

These mapping results plus the results on the statistics of the global HI content described in the last section show that most of the HI seen in ellipticals is not produced by stellar mass loss, but was probably acquired from outside the galaxy. There are several ways in which this might happen. For example, the HI structures seen in the outskirts of some E and S0 galaxies may be due to continued slow infall of primordial gas in a manner similar to the process thought to build the disks in spirals (Gunn 1982). This may be the case for isolated ellipticals like those discussed by Haynes and Giovanelli (1980). Another possibility is that the HI-rich ellipticals acquired their gas via mergers with gas-rich dwarfs or during a tidal interaction with a neighboring gas-rich spiral. Such processes are strongly suggested at least for some galaxies by the unsettled appearance of gas in the outer regions (e.g. NGC1052, NGC5128, NGC1023). The misalignments between the HI and optical structures also suggest that the gas was acquired fairly recently. Approximately equal numbers of E and S0 galaxies have the gas - dust lanes parallel to the major (e.g. NGC5084) or minor (e.g. NGC5128) axes; a similar number have the lanes at large angles to either axis (e.g. NGC4278). These statistics suggest recent capture and settling into one of the two principal planes of the galaxy's potential.

The observation that the HI is often in rings well outside the optical galaxy suggests that in some cases HI may have been ablated from the volume of the galaxy occupied by stars by, for example, the action of stellar winds. In this context, the HI distribution in the large-bulge Sa galaxy NCG4594 is of interest (Bajaja et al. 1984). In this galaxy, the HI is found only in the outer parts of the stellar disk, suggesting that it has been removed from the inner regions of the disk by interaction with winds from the bulge stars. A similar fate may await cold gas accreted to the inner regions of E or SO galaxies.

4. DYNAMICS, MASSES AND MASS-TO-LIGHT RATIOS

The synthesis maps described above show in several cases that the projected circular velocities of the HI structures stay constant over several effective radii, i.e. that E and SO galaxies, like spirals, have "flat rotation curves". Such flat rotation curves are observed for the ellipticals NGC5128 and NGC1052 (van Gorkom, this conference), for NGC4278 (Raimond et al. 1981 and in preparation) and NGC5666 (Lake et al. 1986). Thus, in the outer parts of ellipticals, $\rho \sim r^{-2}$ and the mass-to-light ratio increases with radius. Because the HI is in rings rather than disks in many cases the rotation curve cannot be followed to the inner regions of the galaxy; however, some comparison of the dynamics of the inner and outer regions can be found from an examination of the stellar velocity dispersion and the HI circular velocity. For a spherical galaxy with "dark matter" density $\rho \sim r^{-2}$, the velocity dispersion is constant with radius, as is the circular velocity V_c, and $V_c = \sqrt{2}\,\sigma$, where σ is the one-dimensional velocity dispersion. If the stars in the galaxy have a density distribution $\rho_* \sim r^{-3}$ and the potential is dominated by the dark matter, then σ_*, the one-dimensional stellar velocity dispersion, is also constant with radius and $V_c = \sqrt{3}\,\sigma_*$.

Values of V_c at large radii (5-40 kpc) can be measured from HI maps if the inclination of the HI structure can be found. These estimates can be quite uncertain because of the irregularities in the HI distribution and the low signal-to-noise ratio of the observations. The stellar velocity dispersion in Es and spiral bulges is observed to be roughly constant with radius but often rises at the center of the galaxy (e.g. Kormendy and Illingworth 1982). In Figure 2 V_c(HI) is plotted versus the central velocity dispersion σ_* (from the compilation by Whitmore et al. 1985) for E and SO galaxies for which both measurements are available, plus NGC4594. All of the galaxies lie between the $\sqrt{2}$ and $\sqrt{3}$ lines except NGC3998, whose central velocity dispersion is very large for its luminosity and may indicate the presence of strong anisotropies or the presence of a massive central object. For the galaxy with the lowest value of σ_* and V_c in Figure 2 (NGC7743) no HI map is available; the value of V_c plotted is for the global HI profile width and is therefore a lower limit.

Figure 2 shows that elliptical galaxies have a roughly r^{-2} density dependence, i.e. a flat rotation curve, between approximately a few hundred pc and a few tens of pc. Thus the distribution of matter, both visible and invisible, in ellipticals is controlled by the dark matter distribution in a similar way to the distribution in spirals.

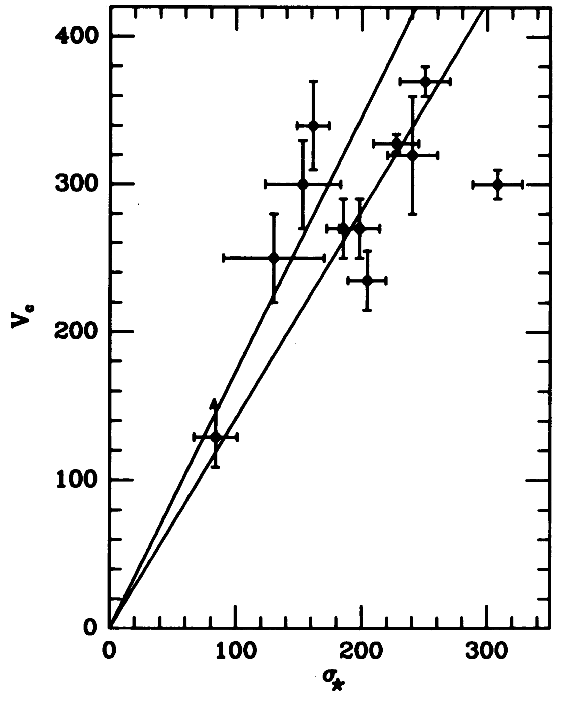

Figure 2. HI circular velocity V_c versus central stellar velocity dispersion σ_* for early-type galaxies. The lines correspond to $V_c = \sqrt{3}\ \sigma_*$ and $V_c = \sqrt{2}\ \sigma_*$.

The masses and mass-to-light ratios can now be estimated for some E and SO galaxies within the observed HI radius and are listed in Table 1. These values are calculated by the present author from values given in the cited literature. The assumed distance and the maximum radius R_m to which HI is detected are also given. The values of M/L_B are in

TABLE 1.

Galaxy	Type	D(Mpc)	R_m(kpc)	$M(M_\odot)$	$\frac{M}{L_B}(\frac{M_\odot}{L_\odot})$	References
N4278	E2	8	7.5	$>1.8\times10^{11}$	>44	Raimond et al. 1981
N5084	SOp	21	45	$>1.1\times10^{12}$	>82	Gottsman and Hawarden 1986
N2787	SO	10	20	$>3.4\times10^{11}$	>85	Shostak 1986
N1052	E4	13	12	$>1.5\times10^{11}$	>17	van Gorkom et al. 1986
N4594	Sa	10	10	$>3.2\times10^{11}$	> 8	Bajaja et al. 1984
N5128	Ep	2	3.5	$>5.1\times10^{10}$	> 6	van Gorkom (this conference)

almost all cases very much higher than the value of ~5 expected for the stars in these systems. The above data show that, in a large-scale sense, E/S0 and spiral galaxies are very similar to each other, except for the larger masses of the ellipticals.

It is of interest to compare these mass estimates with those derived by other methods. Currently, there is no overlap of early-type galaxies well observed in their shell distribution and in HI, and only two galaxies observed in both HI and X-rays, viz. NGC4594 and NGC5128. The HI results for these two galaxies are compared with the X-ray results of Forman, Jones and Tucker (1985) in Table 2. In making the comparison, the distances assumed by FJT were used. FJT calculate the

TABLE 2. Comparison of masses derived from X-ray and HI measurements for NGC4594 and NGC5128.

	NGC4594	NGC5128
Distance	17 Mpc	5 Mpc
R_m(X-ray)	32 kpc	20 kpc
M_T(X-ray)	1.7×10^{12} $M_\odot$	1.2×10^{12} $M_\odot$
"V_c"(X-ray)	480 km/sec	510 km/sec
V_c(HI)	370 km/sec	240 km/sec
R_m(HI)	18 kpc	9 kpc

mass within the maximum radial extent of the X-ray emission by assuming an isothermal gas sphere at the same temperature (1.2×10^7 K) for all galaxies. This is tantamount to assuming a circular velocity of ~500 km/sec at R_m(X-ray) for all galaxies, as shown in Table 2. This value is much higher than the value observed in HI. To be sure, R_m(HI) < R_m (X-ray) for both galaxies, and there is no direct evidence against the amplitude of the HI rotation curve staying constant to R_m(HI) and then rising steeply somewhere between R_m(HI) and R_m(X-ray). Personally I regard this as unlikely and suspect that for these two galaxies at least the X-ray models overestimate the mass. A possible refinement might be made to the X-ray models by scaling the assumed temperature to the observed stellar velocity dispersion.

5. HI AND RADIO CONTINUUM

An intriguing idea suggested by the discovery of cold gas in some ellipticals is that the activity seen in the nuclei of some Es is

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fuelled by cold gas. In this scenario, most large Es contain a central engine, active in the early universe but now quiet because of lack of fuel. Such monsters can obtain a temporary new lease on life if the parent galaxy accretes more fuel at some later time (e.g. Gunn 1979). This hypothesis finds observational support in the perpendicularity of radio jets and gas/dust lanes (Kotanyi and Ekers 1979; Laing 1984) and in the presence of HI in the active Es NGC1052, NGC4278 and NGC5128 (in particular in the redshifted HI absorption components seen for some active nuclei - van Gorkom, this conference). The accumulation of large bodies of HI and continuum data for nearby E/SO galaxies allows this question to be adressed statistically (Knapp and Wardle 1986, in preparation). We find (1) the distribution of P_c/L_B (where P_c is the radio continuum power) is similar for E and SO galaxies, but different for spirals, which show the presence of disk continuum emission caused by star formation activity, (2) for high luminosity galaxies ($L_B >$ 3×10^9 $L_\odot$) the observed presence of HI significantly enhances the likelihood that the galaxy is a radio source, (3) low-luminosity E/SO galaxies ($L_B < 3\times10^9$ $L_\odot$) are not radio sources even when they contain cold gas; it is therefore likely that these galaxies do not contain central engines, (4) the radio power is not proportional to the HI content, i.e. the HI is in a reservoir and the accretion rate to the center does not depend on the total amount of HI present, and (5) we see no evidence in the data for disk emission from E and SO galaxies, i.e. of the presence of massive star formation (although the present limits are not very stringent).

6. THE GAS-TO-DUST RATIO

More and more observations are turning up dust lanes and patches in elliptical galaxies (e.g. Sadler and Gerhard 1985, Ebneter and Balick 1985). Gas-to-dust ratios are hard to estimate from such data because of the unknown relative distributions of the dust and stars. A different approach has been taken by Jura (1986) who found that some nearby Es are detected by the IRAS satelite at 100μ. The gas-to-dust ratios inferred from these observations and the HI data may be similar to that found in the solar neighborhood; a similar result is found for SOs (Jura and Knapp, in preparation). Much more work remains to be done on this subject; in particular the non-detections need to be included, but the current results provide another piece of evidence against the hypothesis that the cold gas is primordial, at least in the inner parts of the galaxies.

Finally, it is worth mentioning molecular gas. Little work has been done on this to date, but positive results include the detection of several species (e.g. H_2CO) in absorption against the nucleus of NGC5128 and the detection of CO emission from NGC185 reported by Wiklind and Rydbeck (1986).

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DISCUSSION

Norman: Could you have missed a substantial amount of gas with velocity dispersions of > 500 km/s?

Knapp: Yes, the observations made up to ~ 5 years ago used HI front– and back ends whose effective velocity coverage was ≤ 1600 km/s, so that very wide HI lines such as you have for the high–luminosity ellipticals might well have been missed. Recently, both Arecibo and NRAO have acquired equipment allowing velocity coverage of > 4000 km/s; the effectiveness of this in detecting HI from very massive gas has been demonstrated recently by Giovanelli and collaborators. So far, to my knowledge, no new HI detections have been made for high–luminosity ellipticals.
A related problem which makes the HI data incomplete is the great difficulty in observing ellipticals which are powerful radio emitters because of the poor spectral baselines caused by the enhanced noise temperature of the "on–source" observation.

Kochhar: We (cf. *Supernovae, their Progenitors and Remnants*, eds G. Srinivasan & V. Radhakrishnan, Bangalore, p. 47, 1985) have suggested that the presence of gas and radio activity in ellipticals is also correlated with the occurrence of supernovae in them. For example, in the Arecibo survey, whereas only 25% of observed galaxies are radiosources, 60% of the ellipticals with supernovae are radiosources.

Sarazin: The number of Type I SN in ellipticals is only about 15, so I don't think one could usefully constrain any SN versus HI correlation.