CO in Early-Type Galaxies

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ABSTRACT. Observations of CO emission in far-IR bright early-type galaxies have shown that a substantial number of them contain 10^7–10^9 $M_\odot$ of molecular gas. The star formation efficiency in these galaxies is as high as in spiral galaxies. The molecular gas has properties similar to that in spirals and is usually distributed in a rotating disk. The origin of the molecular gas is discussed.

1. Introduction

Early-type galaxies, i. e. ellipticals and S0s, have long been considered to be essentially devoid of interstellar matter and star formation activity. The concept of gas-free inert stellar systems is based on the lack of visible tracers of interstellar gas and young, i.e. massive stars. Galaxy formation scenarios suggest that, at least the elliptical galaxies, exhausted their gas reservoir through vigorous star formation during the initial free collapse. This concept has changed during the last few years, as refined observational techniques have shown that early-type galaxies possess an interstellar medium (ISM) comprising the same components as spiral galaxies (c.f. Schweizer, 1987): a *cold component* consisting of dust, atomic and molecular gas (T≈10–100 K), a *warm component* consisting of ionized gas (T≈10^4 K) and a *hot component* (T≈10^7 K).

The bulk of the previously "missing gas" has been found in hot extended gaseous halos, surrounding a majority of ellipticals and S0s, radiating in the X-ray band (Nulsen et al., 1984, Forman et al., 1985; Trinchieri and Fabbiano, 1985). The presence of hot gas is independent of whether the galaxy is isolated or in a cluster. In fact, at a given optical luminosity, galaxies which are brighter in X-rays are found in less dense regions (Sarazin, 1990). The mass of the hot gas is in the range 10^8–10^{10} $M_\odot$, consistent with the present rates of stellar mass loss (Faber and Gallagher, 1976). At least for the more luminous galaxies, the cooling time of the gas suggests the presence of steady-state cooling flows (c.f. Sarazin, 1990).

The presence of ionized gas at temperatures of 10^4 K in early-type galaxies has been known for more than fifty years. In 1936 Mayall detected the [OII] λ3727 emission line in the elliptical galaxy NGC 1052. Today the detection rate of optical emission lines in early-type galaxies is close to 60% (Phillips et al., 1986; Bettoni and Buson, 1987). Less luminous early-type galaxies have emission spectra resembling HII regions, whereas more luminous ones have LINER type spectra (Sadler, 1987). With the advent of linear detectors it is now also possible to construct continuum subtracted Hα images of the central regions of both elliptical and S0 galaxies, showing the presence of relatively large HII regions (Pogge and Eskridge, 1987; Kim, 1989; Bertola et al., these proceedings). Star formation regions have also been observed at 6 cm radio continuum using the

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VLA (Wrobel and Heeschen, 1988). The typical mass of the ionized gas found in early-type galaxies is only of the order 10^4–10^5 M_o (Sadler, 1987).

The cold component has been revealed through observations of HI, far-IR and CO, as well as through optical observations of dust features. Roughly half of the early-type galaxies have optically visible dust lanes (Ebneter and Balick, 1985; Sadler and Gerhard, 1985, Sparks et al., 1986; Ebneter et al., 1988). HI surveys have shown that about 15% of Es, 25% of S0s and 40% of S0/a's contain observable amounts of HI gas (Knapp et al., 1985; Wardle and Knapp, 1986), with typical masses between 10^7–10^9 M_o. IRAS co-added data lead to detection of far-IR emission in about 50% of the early-type galaxies (Jura et al., 1987; Knapp et al., 1989). If the far-IR emission in the early-type galaxies is, as in spiral galaxies, mainly reradiated UV photons from young and massive stars (that this is most probably the case even for radio galaxies has been shown by Knapp et al., 1990), then the inferred dust masses correspond to 10^8–10^9 M_o of molecular gas. Observations of CO emission in early-type galaxies have now also shown that a substantial number of them do possess molecular gas, with H_2 masses in the range predicted by the far-IR fluxes.

Thus, all the ISM components present in spiral galaxies have also been observed in a large number of early-type galaxies. However, in the early-type galaxies the ISM seems to have reached a quite different equilibrium than that in spirals. The rest of this review concerns observations of the coldest and densest part of the ISM in early-type galaxies, as revealed through observations of CO. In §2 the CO surveys and global properties of the molecular gas and the inferred star formation properties are discussed, in §3 a few individual early-type galaxies are presented, in §4 the physical state and the origin of the molecular gas are discussed and finally, in §5 the results are summarized.

2. CO surveys and global properties

2.1 SURVEYS

The search for molecular gas in early-type galaxies started soon after the first detection of extragalactic CO emission. In 1976, Faber and Gallagher reported upper limits on 4 early-type galaxies, and in 1979 Johnson and Gottesman presented limits on 9 more. The implied limits on H_2 masses were in most cases well above 10^9 M_o. Following the detection of cluster cooling flows, a few searches of molecular gas in clusters were done (c.f. Bregman and Hogg, 1988; Grabelsky and Ulmer, 1990), but none were detected in CO. Again the limits implied H_2 masses above 10^9 M_o.

The first early-type galaxies to be detected in CO were the dwarf elliptical NGC 185 (Wiklind and Rydbeck, 1986), which has a minuscule 10^5 M_o of H_2, and the S0 galaxy NGC 404, with $7 \cdot 10^7$ M_o of H_2 (Wiklind and Henkel, 1990a). These galaxies were selected from morphological considerations only, i.e. the presence of dust and anomalous colours. The first succesful surveys of CO emission in early-type galaxies (Sage and Wrobel, 1989; Thronson et al., 1989; Wiklind and Henkel, 1989) used the IRAS catalog and the compilation of co-added IRAS data by Knapp et al. (1989) for choosing candidate galaxies. This proved to give a detection rate of about 50% for Sage and Wrobel and Thronson et al., and even higher for Wiklind and Henkel. The total number of early-type galaxies observed in CO, including unpublished detections, now amounts to 50. Some of these might be misclassified spirals, but the large majority are true early-types. Of the detected galaxies 10 are classified as ellipticals, 2 as E/S0 and the rest (38) as S0 or S0/a's. Since the selected galaxies have a clear bias toward far-IR bright objects, and since few siginificant upper limits exist, it is impossible to estimate the true rate of occurence of molecular gas in these galaxies. However, the early-type galaxies seem to follow the same M(H_2) vs. L_{FIR} relation as spiral galaxies (Figure 1), implying that galaxies with L_{FIR} above 10^7 L_o (~50% of all early-type galaxies) contain

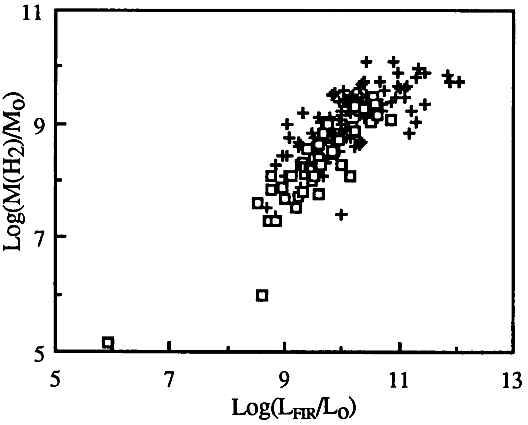

Figure 1. The H_2 mass vs. the far-IR luminosity for early-type galaxies (squares) and a sample of spiral galaxies (crosses).

more than 10^6 M_O of molecular gas. An unbiased survey of the molecular gas content of early-type galaxies is underway (Wiklind and Henkel, unpublished).

2.2 GLOBAL PROPERTIES

In Wiklind and Henkel (1989), the CO, far-IR and optical properties of the detected early-type galaxies were compared with a sample of 120 spiral galaxies selected from the literature. The sample of spiral galaxies contain, as does the early-type sample, both field and interacting systems. The results were that the early-type galaxies have, on average, an order of magnitude less H_2 mass and far-IR luminosities than the spirals. Using the far-IR luminosity as a measure of the current star formation rate (SFR) (c.f. Thronson and Telesco, 1986), the typical SFR for the early-type sample is found to be 1 M_O yr^{-1} or less. However, the ratio $L_{FIR}/M(H_2)$, which is a crude measure of the current star formation efficiency (SFE), is similar for the two samples.

This comparison was based on 24 detections, some of them tentative. It is therefore worthwhile to redo the comparison with an early-type sample twice as large. The new data also includes 15 early-type galaxies that have been mapped, so that most of the detectable CO emission have been included. However, the sample is still biased towards far-IR bright objects. In Figure 2a-c, the distributions of $M(H_2)$, L_{FIR} and SFE for the early-type galaxies are compared with the same spiral sample as used in Wiklind and Henkel (1989). As can be seen from the figures, the conclusions about the distributions hold true for the enlarged early-type sample.

There are no compelling evidence that the far-IR emission in early-type galaxies should not originate from dust emission. In an IRAS colour-colour diagram (Figure 3), the distribution of the early-type galaxies are indistinguisable from that of the spirals. Thus, the similarity of the SFE distributions for the early-type and spiral sample implies that, when massive star formation is taking place in early-type galaxies, it does so with an efficiency similar to that of spiral galaxies. Hence, on a global scale, the presence of spiral arm density waves is not necessary for massive star formation. As discussed by Knapp (1990), star formation is essentially a small scale process, with an efficiency seemingly unrelated to global properties of the parent galaxy.

HI masses are known for 27 of the early-type galaxies detected in CO. Excluding the exceptional galaxy NGC 1275, two Virgo Cluster members (which are deficient in HI) as well as NGC 404, which has an uncertain HI mass, the average $M(H_2)/M_{HI}$ ratio becomes 0.7. This is in marked contrast with the result of Young and Knezek (1989) who found a ratio of approximately 4.

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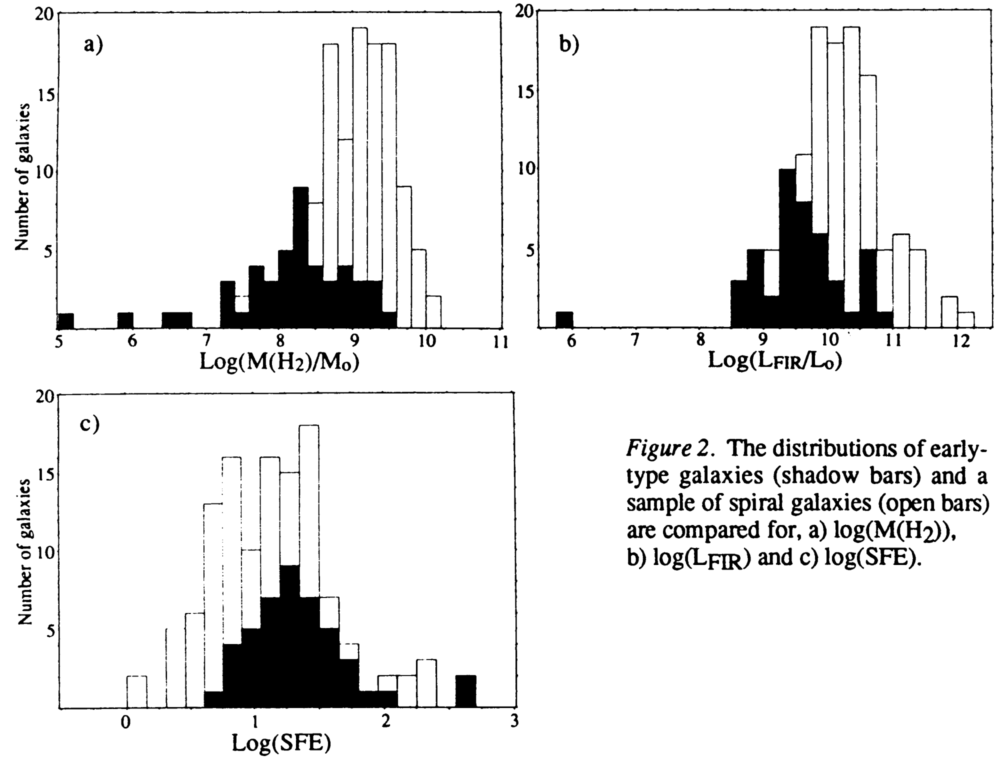

Figure 2. The distributions of early-type galaxies (shadow bars) and a sample of spiral galaxies (open bars) are compared for, a) $\log(M(H_2))$, b) $\log(L_{FIR})$ and c) $\log(SFE)$.

3. Individual galaxies

Apart from the surveys of CO in early-type galaxies mentioned above, there have been searches for CO in more specific galaxies. Huchtmeier et al. (1988) detected CO at a position 1' south of the center in NGC 4472. Gordon (1990) detected $5 \cdot 10^7$ $M_\odot$ of H_2 in the blue elliptical NGC 3928. Dupraz et al. (1990) find $2 \cdot 10^9$ $M_\odot$ of H_2 in the peculiar galaxy NGC 7252. This galaxy has been classified as being both an old merger remnant and a young elliptical galaxy. It has two well-developed stellar tidal tails, a signature of the merging of two disk galaxies, and a light distribution that follows the $r^{1/4}$ law. Maintaining the present star formation rate, the molecular gas will be exhausted in less than $3 \cdot 10^8$ years, and NGC 7252 will then take the appearance of a normal elliptical galaxy. The powerful radio galaxy NGC 1275 (Perseus A) has been observed in CO by Lazareff et al. (1989) and Mirabel et al. (1989). This galaxy is a bright X-ray source, with a cooling flow depositing about 200 $M_\odot$ yr^{-1} of gas into the galaxy. Comparing the central emission profiles observed with the IRAM and NRAO telescopes, the line intensities are consistent with an unresolved source, with an estimated H_2 mass of $2 \cdot 10^9$ $M_\odot$. The molecular gas seems to be associated with Hα filaments, but the velocity dispersion of the molecular gas is less than that of the ionized gas.

A number of early-type galaxies have now also been mapped in some detail, giving information on the distribution and kinematics of the molecular gas. One of the prime objects, Cen A (NGC 5128), has been observed by several groups (Phillips et al., 1987; Israel et al., 1990; Eckart et al., 1990a,b). Cen A has normal CO, HI and far-IR properties when compared to the rest of the early-type galaxy sample. This galaxy is discussed in more detail by Eckart (these proceedings). The S0 galaxy NGC 404, which contains HI gas, far-IR flux and several prominent dust lanes, has been mapped in both the J=1-0 and J=2-1 lines of CO by Wiklind and Henkel (1990a). The molecular gas in NGC 404 is distributed in a ring-like structure around the nucleus. HI observations with the VLA (Wiklind and Henkel, unpublished) reveals that also the HI gas is situated in a ring structure. However, whereas the molecular gas is found in the center region, the HI ring sits at the edge of the optical disk (Figure 4). Very little HI gas is found inside the Holmberg radius. The S0/a galaxy NGC 3593 has also been mapped in the J=1-0 and J=2-1 lines of CO (Wiklind and Henkel,1990b). Comparison of the kinematics of the ionized, the HI and the molecular gas shows that, apart from effects of different angular resolutions, the velocity structure seems to be the same for all three ISM components. Finally, NGC 5195, the small SB0 companion to M 51, has been mapped by Sage (1989, 1990). In this rather special galaxy he finds evidence for two velocity components in CO: one associated with NGC 5195 and the other with the overlaying spiral arm from M 51.

There also exist several unpublished maps. For instance, Wiklind and Henkel (in preparation) find a molecular bar structure in the S0/a galaxy NGC 4369, and a molecular disk, inclined relative to the stellar disk, in the S0 galaxy NGC 7213. In general, the molecular gas in early-type galaxies is distributed in a disk, with kinematical properties of normal disk rotation, i.e. a steeply rising rotation curve in the inner parts and flat in the outer parts.

Name	Type	I_{12}/I_{13}	I_{21}/I_{10}
NGC 404	S0	11	0.5
NGC 1275	E	—	0.5
NGC 1317	S0/a	—	0.6
NGC 1546	S0/a	—	0.7
NGC 3593	S0/a	5	1–0.5
NGC 4369	S0/a	—	0.5
NGC 4691	S0/a	—	0.6
NGC 4710	S0	8	0.7
NGC 4940	S0	—	0.6
NGC 5128	Ep	6–13	0.6
NGC 5195	SB0	25	0.5
NGC 7252	Ep	—	0.5

Table 1. Isotope- and J=2-1/J=1-0 intensity ratios for early-type galaxies.

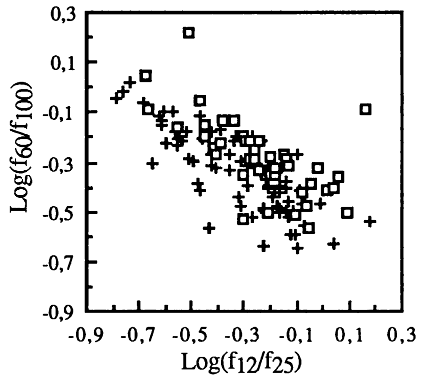

Figure 3. An IRAS colour-colour diagram for early-type galaxies (squares) and a sample of spiral galaxies (crosses).

4. Physical properties and origin of the molecular gas

4.1 PHYSICAL PROPERTIES

So far there is only a limited amount of data on the properties of the molecular gas in early-type galaxies. In Table 1 early-type galaxies with known J=2-1/J=1-0 line intensity ratio are listed. For a

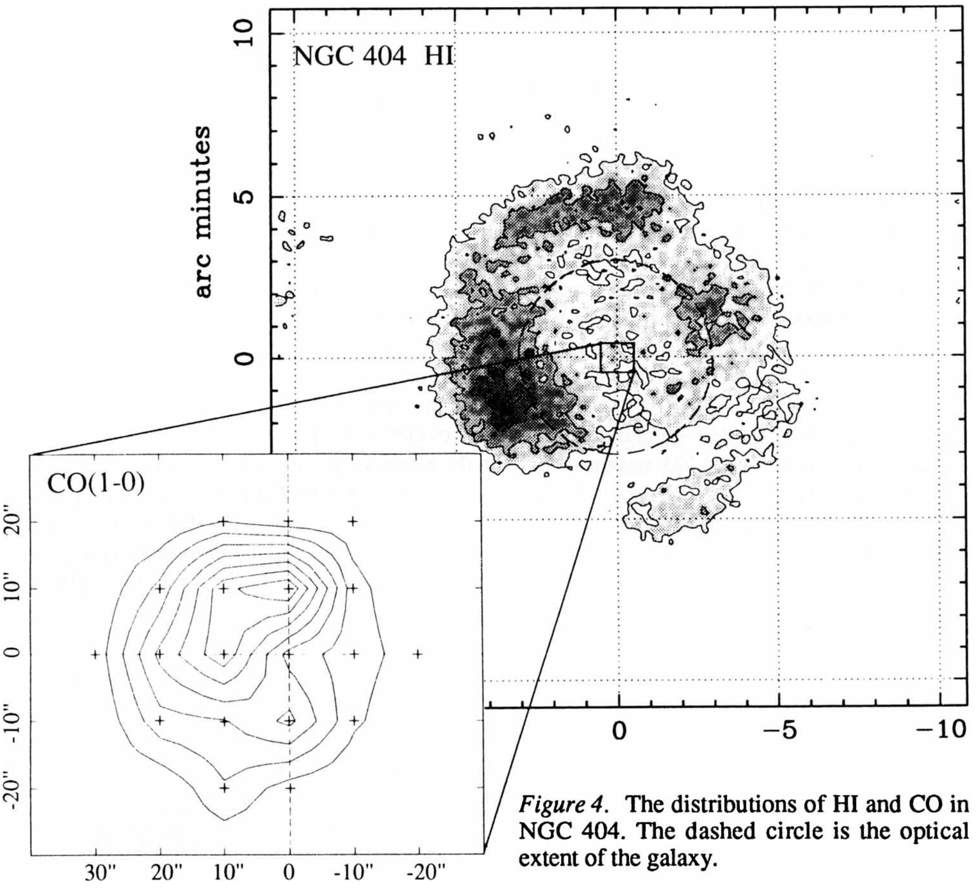

Figure 4. The distributions of HI and CO in NGC 404. The dashed circle is the optical extent of the galaxy.

few of these the $^{12}CO/^{13}CO$ intensity ratio is also known. For NGC 5128 (Cen A) there are additional molecular line absorption data (Eckart, these proceedings).

Table 1 tells us that the molecular gas in early-type galaxies have optically thick ^{12}CO emission and J=2-1/J=1-0 ratios close to 0.5, which is similar to spiral galaxies (c.f. Casoli, these proceedings). A J=2-1/J=1-0 intensity ratio significantly less than one is usually interpreted as a very cold (T_K<10 K) thermalized gas. However, an intensity ratio of 0.5 can also be achieved for a diffuse CO gas, with $n(H_2) \approx 10^2$ cm^{-3}. At these low densities the intensity ratio is almost independent of the kinetic temperature of the gas. Hence, the molecular ISM component in early-type galaxies seems to be very similar to that found in ordinary spirals.

4.2 ORIGIN OF THE MOLECULAR GAS

There are at least four possible sources for the molecular gas observed in early-type galaxies: (i) remnant gas from the galaxy formation epoch, (ii) stellar mass loss, (iii) gas capture from neighbouring gas-rich galaxies, and (iv) cooling flows.

Remnant gas. If the observed ISM in early-type galaxies is remnant from the epoch of galaxy formation, the star formation activity has to be intermittent. Continuous star formation during 10^{10}

Table 2. CO, far-IR and X-ray properties of early type galaxies

Name	L_{FIR} $L_{\odot}$	L_X $L_{\odot}$	$M(H_2)$ $M_{\odot}$	M_X $M_{\odot}$	$\dot{M}_x/\dot{M}_{FIR}$	τ_g 10^8 yrs	τ_X
NGC 1316	$2.0\cdot10^9$	$5.7\cdot10^6$	$2.1\cdot10^8$	$1.8\cdot10^8$	0.6	3	5
NGC 3593	$2.5\cdot10^9$	$4.4\cdot10^5$	$3.7\cdot10^8$	$1.4\cdot10^8$	0.04	5	19
NGC 4459	$1.0\cdot10^9$	$1.1\cdot10^6$	$4.7\cdot10^7$	$3.5\cdot10^8$	0.2	1	12
NGC 4649	$3.3\cdot10^8$	$1.8\cdot10^7$	$4.1\cdot10^7$	$5.8\cdot10^9$	11	4	3
NGC 5128*	$6.8\cdot10^9$	$1.2\cdot10^6$	$2.8\cdot10^8$	$4.3\cdot10^8$	0.04	1	11
NGC 5866	$1.6\cdot10^9$	$5.6\cdot10^5$	$3.7\cdot10^7$	$2.0\cdot10^8$	0.07	0.7	16

*) Non-nuclear component of NGC 5128

years would give broad band colours inconsistent with those observed. In dwarf galaxies episodic star formation is a fact of life, and if star formation is a small scale process this could also be the case for early-type galaxies, which have cold gas masses comparable to dwarf galaxies.

Stellar mass loss. Direct conversion of stellar mass loss to molecular gas is probably not possible in elliptical galaxies, where the stellar velocity dispersion is high enough to heat the expelled gas to temperatures of 10^6 to 10^7 K. In S0 galaxies where the stellar velocity dispersion is much lower, this source of the molecular gas can not be ruled out.

Gas capture. In several early-type galaxies where the HI gas has been mapped in detail, the specific angular momentum of the gas has been found to be higher than that of the stars (Raimond et al., 1981; van Gorkom et al., 1986; van Driel, 1987), or even counter-rotating relative to the stars (Schweizer et al., 1989). Counter-rotation has also been found in the ionized gas (Caldwell et al., 1986; Galetta, 1987; Bertola and Bettoni, 1988; Schweizer et al., 1989). This is generally taken as evidence of an external origin of the gas. So far, the only indications of discrepant kinematics between the old stellar population and the molecular gas are found in Cen A, where the angular momentum vector of the molecular disk is perpendicular to that of the underlying E galaxy (c.f. Schweizer, 1987), and in the face-on S0 galaxy NGC 7213, where the molecular gas seems to be situated in a rotating disk inclined about 50° relative to the stellar disk (Wiklind and Henkel, in preparation). However, the fact that an ISM seems to be a pervasive feature of early-type galaxies (albeit in very small amounts), and that it is observed in several apparently isolated systems, put a lot of strain on the gas-transfer scenario.

Cooling flows. If cooling flows are refueling the ISM of early-type galaxies there should be a correlation between X-ray and molecular as well as far-IR properties. No clear correlations of this kind has been found (Knapp, 1990; Sarazin, 1990).

In Table 2 mass loss rates from cooling flows are compared with SFRs derived from the far-IR luminosity (Thronson and Telesco, 1987), assuming that 50% of the L_{FIR} stems from star forming regions. Furthermore, the cooling time of the X-ray gas (τ_X) is compared with the molecular gas consumption time (τ_g). Properties of the X-ray gas and cooling flows have been derived using the formalism in Nulsen et al. (1984) and Thronson et al. (1989), assuming a gas temperature of 10^7 K and an X-ray core radius of 5 kpc. The ratio of the mass loss rate of the X-ray gas and the SFR can be approximated with $\dot{M}_x/\dot{M}_{FIR} \approx 200\cdot(L_X/L_{FIR})$. From Table 2 it is clear that 3 out of 6 galaxies have $\dot{M}_x/\dot{M}_{FIR}$ ratios which are much less than 1 (NGC 3593, NGC 5128 and NGC 5866). In these galaxies a steady-state cooling flow can not be the source of the molecular gas and the inferred star formation. In these galaxies the cooling time of the hot gas is much longer than the molecular gas consumption time. For NGC 1316 refueling of the ISM from cooling flows can not be ruled out from the $\dot{M}_x/\dot{M}_{FIR}$ ratio. NGC 4459 is a borderline case, however, here the cooling time of the hot gas is an order of magnitude longer than the molecular gas consumption time. This seems to exclude a steady-state situation. For NGC 4649 the ratio $\dot{M}_x/\dot{M}_{FIR}$ is 11, whereas the time scales are comparable. A possible explanation for this is a high-mass truncation of the IMF. Hence, with the assumption of a steady-state situation, it seems that it is only in NGC 1316 and NGC 4649 that cooling flow can be a source of the molecular gas.

From the discussion above it is clear that no consensus can be achieved regarding the origin of the molecular gas in early-type galaxies. It is possible that the different ISM components, especially the hot and the cold, have different origins.

5. Summary

Observations during the last few years have shown that a substantial number of early-type galaxies possess a cold and dense molecular gas component, with H_2 masses in the range 10^7–10^9 $M_\odot$. The H_2 masses and the far-IR luminosities of the early-type galaxies are, on average, an order of magnitude lower than for ordinary spirals. However, the distributions of the $L_{FIR}/M(H_2)$ ratios are similar for both early-type and spiral galaxies, implying that massive stars form with an efficiency independent on global properties, such as the presence of density waves. The average $M(H_2)/M_{HI}$ mass ratio is close to one for the early-type galaxies.

Detailed mapping of the distribution and kinematics of the CO emission in a number of early-type galaxies have shown the molecular gas to be distributed in rotating disks. In at least one case the molecular disk is considerably inclined relative to the stellar disk. Observations of $^{12}CO/^{13}CO$ ratios and J=2-1/J=1-0 line intensity ratios indicates that the molecular gas in early-type galaxies is similar to that in ordinary spirals.

No clear consensus regarding the origin of the molecular gas in early-type galaxies can be achieved. Steady-state cooling flows seems to be excluded in some cases, but not in others. The popular belief that the gas has an external origin is questioned on the premise that a large number of early-type galaxies, including several isolated systems, appear to have an ISM.

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