Cold Gas and Star Formation in Elliptical Galaxies

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Abstract. Elliptical galaxies outside dense clusters are observed to contain small amounts (relative to spiral galaxies) of cold interstellar gas. This review discusses the atomic gas, the molecular gas, and the dust in elliptical galaxies. Field elliptical galaxies contain about 0.01 to 0.1 of the cold interstellar matter content of spiral galaxies of similar luminosity, and support a low level of star formation. The surface densities of cold gas clouds in the centers of some elliptical galaxies are comparable to those in the densest regions of the Galactic disk. These observations suggest that elliptical galaxies in the field, like spiral galaxies, have a long-lived interstellar medium which evolves with the galaxy. The timescale for star formation, however, appears to be much shorter, leaving these systems with little gas at the present epoch.

1. Introduction

Cold gas is the ‘living’ part of any galaxy, its bloodstream, so to speak. Stars form from this gas and in turn eject processed material to the interstellar medium, a symbiotic process which dominates the evolution of spiral galaxies to the present day. Twenty years ago, elliptical galaxies were thought to be simple systems, consisting of a single age stellar population formed in a single event at some long-ago epoch and passively evolving ever since (Tinsley & Gunn 1976). The puzzle of what had become of the gas shed by evolving stars (Faber & Gallagher 1976) was thought to be solved by the observation of large amounts ($10^9$ to $10^{10} M_\odot$) of hot ($10^6$ to $10^7$ K) gas in extended halos around elliptical galaxies by the EINSTEIN and, more recently, ROSAT and ASCA observatories (e.g. Canizares et al. 1987). However, as shown by several papers at this conference, for example, the observed gas accounts for only a small fraction of the expected total. Hot gas does not directly support star formation. Nevertheless, as the discussion at this conference shows, there is not yet a comfortable consensus on the origin of the hot gas, nor on the fate of the gas produced by stellar evolution, nor on the relationship between cold and hot gas in these systems.

Even in 1976, it was known that some elliptical galaxies contain substantial amounts of cold interstellar gas, visible as dust lanes and patches: the paradigm galaxy is NGC 5128, the powerful nearby radio galaxy Centaurus A. However, since the morphological definition of elliptical galaxies includes “smooth appearance” with no discernible structure, such galaxies were classified as “Ep”, “SO”, “SOp”, or “I0”, where p = peculiar. Galaxies like NGC 5128 were considered to
be involved in a merger with a gas-rich spiral galaxy and to be highly atypical elliptical galaxies, or not elliptical galaxies at all.

A lot has changed in the last 20 years, as the observational data at all wavelengths have improved dramatically. Not only has it been found that the stellar populations and abundances in elliptical galaxies trace a varied and complex star formation history, but tracers of ongoing star formation and of many phases of the interstellar medium have been found in a large enough number of systems that these might be regarded as part of the ‘typical’ elliptical galaxy. Nevertheless, both current star formation activity and cold interstellar gas are present in much smaller amounts in elliptical galaxies and hence are much more difficult to distinguish against the galaxy’s background - paradoxically, these phenomena are easier to measure in spiral galaxies because they dominate the radiation from the typical spiral galaxy at essentially all wavelengths.

\( \text{H} \alpha \) emission from warm photoionized gas is a reliable tracer of star formation activity in spiral galaxies, but in ellipticals is also produced by powerful AGNs and by photoionization by the old stars. Hot \(( \geq 10^6 \text{ K})\) gas is produced by supernova shock heating in spiral galaxies and coexists intimately with the cold ISM - but any such gas in elliptical galaxies is completely insignificant compared to the hot gas halos. Diffuse weak radio continuum emission reliably traces star formation in the disks of spiral galaxies, but is insignificant compared to the powerful radio emission from AGNs, which are present in almost all elliptical galaxies. And finally, the spectroscopic and photometric signatures of recent star formation are hard to distinguish against the bright ambient stellar population.

Cold gas itself is more straightforward. HI, usually in very extended structures, has been mapped via its 21 cm emission from several tens of elliptical galaxies. Molecular gas is detected in a surprisingly large fraction of elliptical galaxies via its emission in the CO rotational lines (and, in a few galaxies, via several other molecular probes). Dust is detected in lanes in optical color images, via polarization and color gradients in the optical light (Wise & Silva 1996), and via emission at mid- and far-infrared and submillimeter wavelengths. The most sensitive probe is probably fine structure emission from [CII] and [OI] (Malhotra et al. 1998). Together, these observations show that elliptical galaxies, like spiral galaxies, contain an active cold interstellar medium. This review will discuss these probes of the interstellar medium in turn; the amount, distribution and origin of the interstellar gas, and its relationship to the evolution of elliptical galaxies. It will not discuss the use of HI maps to measure the mass distributions of elliptical galaxies, and will mention only in passing cold ISM at high redshifts and the ISM in radio galaxies, two areas in which a lot of important and vital work has been done recently.

2. HI in Elliptical Galaxies

This subject has really taken off in recent years, thanks to deep single-dish surveys (Huchtmeier 1994, Huchtmeier et al. 1995), and large scale mapping observations using the large southern and northern radio synthesis arrays, the Australia Telescope (AT) and the Very Large Array (VLA). The exciting work from the former telescope is described at this conference in papers by T. Oost-
erloo and R. Morganti. The general subject, as well as recent VLA work, is discussed in recent reviews by Schiminovich et al. (1998a,b), van Gorkom (1998), and van Gorkom & Schiminovich (1998).

Table 1. HI Detection Rates in Early-Type Galaxies.

| Type      | Number | Detected |
|-----------|--------|----------|
| E         | 64     | 5%       |
| E/S0      | 23     | 17%      |
| S0        | 103    | 20%      |
| Ep, S0p   | 20     | 45%      |
| S0a, S0ap | 35     | 43%      |
| Sa, Sap   | 103    | 78%      |

Table 1 shows the detection rates for early-type galaxies from the Revised Shapley-Ames Catalogue (Sandage & Tammann 1981) compiled by van Gorkom (1998). The detection rate rises steadily towards later-type galaxies, and is very small for elliptical galaxies. The detection rate is far higher for ‘peculiar’ galaxies, which are strongly preferentially to be found in the field. Mapping observations with the AT of dwarf and dust lane elliptical galaxies (Oosterloo, this conference: Morganti, this conference) and of shell galaxies by Schiminovich et al. (1994, 1995, 1998a,b,c) give high detection rates - 8/11 in the former case, 12/22 in the latter, statistics from van Gorkom (1998). Early synthesis array HI maps of HI rich elliptical galaxies often showed warped and inclined structures, suggestive of recent acquisition; however, the high HI detection rate, and the regularity of HI disks and rings in many other galaxies, is more compatible with an intrinsic origin for the HI. It will be argued in subsequent sections that the dust and molecular gas content of elliptical galaxies also support this contention: but the particular peculiarity of HI in elliptical galaxies is its large observable extent. Many pieces of evidence for spiral galaxies suggest continued infall of gas from large radii - this infall may also be part of the evolution of elliptical galaxies and responsible for the large HI structures. Where would such gas come from? Dense clusters of galaxies today contain 5 - 10 times as much mass in hot intercluster gas as in stars, with the total amount of normal matter more or less in agreement with the amount at high redshift measured by Ly-α absorption. However, in the field, only a fraction (1/5 or so) of that mass is presently in stars. Cen & Ostriker (1998) suggest that most of the normal matter in the field in the present-day Universe is in the form of diffuse gas heated to temperatures in the hard-to-observe range of $10^5 - 10^7$ K by gravity. If this reservoir provides gas infalling to spiral galaxies, then such gas should also be accreted by elliptical galaxies in the field, and may be the source for the large HI structures and be part of a continually-evolving interstellar medium.

3. Dust: Far-Infrared and Submillimeter Emission

Interstellar dust heated by starlight radiates at far infrared wavelengths, and dominates the emission from essentially all spiral galaxies at wavelengths longer
than a few µm. Long wavelength emission is also detected towards a significant fraction of early-type galaxies by IRAS (12µm, 25µm, 60µm and 100µm), ISO (between about 5µm and 200 µm; Malhotra et al. 1998, S. Madden, this conference) and at submillimeter wavelengths. The largest sample available is from the IRAS survey. These data suggest the presence of small amounts of interstellar dust, and hence of cold interstellar gas, in many nearby elliptical galaxies. However, the data are difficult to interpret because the observed flux densities are low and at only a few times the r.m.s. noise level, and are difficult to distinguish from other sources of emission. At 12µm and 25µm, emission can arise from hot (small) interstellar dust grains; hot (several 100 K) dust in the vicinity of an AGN (these being common in elliptical galaxies); stellar photospheres; and circumstellar dust produced by mass loss. In most elliptical galaxies, the bulk of the emission at these wavelengths seems to be due to stars and circumstellar dust (Knapp et al. 1992). At 60µm and 100µm, emission can arise from cool interstellar dust, non-thermal synchrotron emission from an AGN (cf. the discussion of M 87 by Knapp et al. 1990 and Braine & Wiklind 1993), confusion with nearby dust-rich galaxies, and structure in the Galactic cirrus. Knapp et al. (1989) report the detection of 60µm and 100µm emission from some 40% of elliptical galaxies brighter than 14m, in reasonable agreement with the fraction of elliptical galaxies in which optical dust lanes are seen (Ebneter et al. 1988; van Dokkum & Franx 1995); the infrared fluxes show no correlation with optical brightness. However, because of the several possible/likely sources of contaminating emission, this is an upper limit on the percentage of galaxies with detectable dust emission - Bregman et al. (1998) find that the percentage is much lower, about 15%.

Broad-band spectral energy distributions have been measured for several galaxies using IRAS, ISO and the submillimeter telescopes (IRAM, JCMT and CSO) (e.g. Wiklind & Henkel 1995; Knapp et al. 1998a). These observations show that the emission, including the submillimeter emission, comes from the inner regions (≤ r_e) of the galaxies, and that there is no evidence for cold dust. Cold dust at large distances from the center of the galaxies is by no means ruled out, but the submillimeter emission which is observed comes from the inner regions. The inferred column densities of cold ISM are high, > 10 M☉ pc⁻² in some cases (cf. the CO observations of NGC 3928 by Li et al. 1994). This is higher than in the Galaxy’s molecular ring. The small central disks recently found in the inner regions of early type galaxies also have very high central surface densities (e.g. Scorza & van den Bosch 1998), and may have formed from these dense gas structures.

A rather odd correspondence between HI and infrared emission is found. Galaxies with detectable 60/100µm emission are much more likely to have detectable HI, and vice-versa; but the fluxes are essentially uncorrelated. As we discuss below, the dust and molecular gas are quite tightly correlated. A likely explanation is that the presence of any one of these indicators: dust absorption or emission, HI, or CO, in a galaxy shows that cold interstellar gas is present in all its phases; but since the distributions of the atomic and molecular gas are different, the total amounts observed are not well correlated.
4. Molecular Gas

The subject of molecular gas in elliptical galaxies has been reviewed in detail by Henkel & Wiklind (1997) and by Rupen (1998). As is the case for spiral galaxies, the workhorse molecule is CO. Several largish surveys of nearby early-type galaxies in the CO(1–0) or CO(2–1) lines have been completed in recent years by Wiklind & Henkel (1989), Lees et al. (1991), Wiklind, et al. (1995), and Knapp & Rupen (1996), and CO emission has been detected from some tens of galaxies. In addition, possible CO absorption has been seen in a few galaxies with flat-spectrum compact radio nuclei, most notably NGC 5128 (Israel et al. 1991). The CO(2–1) observations of NGC 1052 reported by Wiklind et al. (1995) and Knapp & Rupen (1996) tentatively show CO absorption towards the nucleus, and the presence of dense molecular gas in its inner regions is also shown by the detection and mapping of powerful H$_2$O maser emission (Claussen et al. 1998).

It should be emphasized that, like the infrared emission, the CO data for elliptical galaxies are not, at present, individually very reliable (with a few exceptions). The lines are weak, and are typically observed with spectrometers covering only about 700 km s$^{-1}$, so that any very broad line emission is likely not to be detected. Some detections have been confirmed using several different telescopes, and some few galaxies (see, e.g. the papers by L. Young and J. Cepa, this conference) have been mapped in detail with interferometers. However, many other detections are tentative; indeed, the field awaits the construction of sensitive and versatile arrays such as the Millimeter Array, which is to be built on Cerro Chajnator, Chile. Nevertheless, the presence of dense molecular gas in a significant number of elliptical galaxies is secure. Table 2 shows the detection statistics, from the concatenation of the above surveys and other CO observations of early-type galaxies, compiled by Rupen (1998). Column 1 contains the galaxy morphological type, column 2 the number of galaxies observed, and column 3 the percentage detection rate. In keeping with the discussion in Section 3, the “peculiar” Es and S0s are folded in with other members of the class. Table 2 shows that the detection rates rise steadily towards later morphological types. If the strength of the CO emission is related to molecular gas in elliptical galaxies in the same ratio as is inferred for spiral galaxies, the molecular gas masses range from $3 \times 10^5$ M$_\odot$ to several $\times 10^8$ M$_\odot$. Lees et al. (1991) show that the molecular gas mass normalized to the blue luminosity also increases steadily towards later morphological types.

| Type   | Number | Detected |
|--------|--------|----------|
| E      | 61     | 39%      |
| dE     | 4      | 100%     |
| E/S0   | 26     | 31%      |
| S0     | 43     | 47%      |
| S0a    | 22     | 55%      |
Figure 1. CO line flux (in units of \( K \times \text{km s}^{-1} \text{arcsec}^2 \), see text) versus total corrected blue magnitude \( B^o_T \) for samples of spiral and elliptical galaxies. The filled circles show the data for the Sb/Sbc galaxies from the sample observed by Elfhag et al. (1996). The open symbols show the data from the sample of elliptical galaxies observed by Lees et al. (1991) and Knapp & Rupen (1996). The inverted triangles show the upper limits on the CO flux for galaxies in which CO was not detected: the limits on the line intensity are calculated as the channel-to-channel r.m.s. noise multiplied by 300 km s\(^{-1}\).
Figure 1 shows the comparison between the molecular gas content of elliptical and spiral galaxies; the CO line flux $S(\text{CO})$ is plotted against the total blue magnitude $B_T$. The CO line flux is in rather arbitrary units: $S(\text{CO}) = I(\text{CO}) \theta^2$, where $I(\text{CO})$ is the integrated line intensity in K $\times$ km s$^{-1}$ and $\theta$ is the half-power beamwidth of the telescope used to make the observations. The comparison sample of spiral galaxies consists of the Sb/Sbc galaxies from the survey of Elfhag et al. (1996), while the CO data are from observations with the Caltech Submillimeter Observatory by Lees et al. (1991) and Knapp & Rupen (1996). The CSO observations are made in the CO(2–1) line with a half-power beamwidth of 30″, and were made only at the central position of the galaxy. The Elfhag et al. observations were made with beamwidths of 33″ or 44″ of the CO(1–0) line, and again were made only at the central position of the galaxy. The use of the CO(1–0) line for one sample and the CO(2–1) line for the other should not pose too much of a problem, because in Galactic molecular clouds, at least, the brightness temperatures of molecular clouds in the two lines are essentially equal.

Figure 1 shows that, on the average, the CO fluxes are 20 - 30 times lower in elliptical galaxies than in spiral galaxies of the same total blue magnitude - elliptical galaxies contain a lot less dense cold gas. Note also the large scatter in the CO flux densities of the elliptical galaxies and the complete lack of correlation between the CO flux and the blue light. Many of the CO observations have resulted only in upper limits on the CO fluxes, as shown in Figure 1. The values of the upper limits overlap completely with those of the detections; statistical analysis of data sets with this sort of mix of detections and upper limits (see Lees et al. 1991, for example) show that the upper limits are not restrictive: in other words, the data are consistent with all elliptical galaxies having weak CO line emission and hence small amounts of molecular gas.

Figure 2, where the CO fluxes are plotted versus the 100μm fluxes for the same two samples of galaxies, tells a different story. Although the beam used to observe the 100μm flux densities is large (about 3′ × 7′) and therefore observes most of the 100μm emission (and further the 100μm data plotted in Figure 2 include total flux densities for extended galaxies, taken from NED), the CO and 100μm emission are fairly tightly correlated for the spiral galaxies, unlike the case with blue light (Figure 1). Figure 2 suggests a fairly well-mixed dense interstellar medium in these galaxies, with a roughly constant gas to dust ratio. The same data are also plotted for the sample of elliptical galaxies. Although the scatter is much larger for these low signal-to-noise ratio observations, the measurements for the elliptical galaxies lie on the same relationship as found for spiral galaxies. The dotted line in Figure 2 shows a relationship of slope 1, i.e. $S(\text{CO}) \propto S(100\mu\text{m})$. Thus most of the 100μm flux in these systems is associated with the molecular interstellar medium, and the global characteristics of the dense ISM are roughly the same in elliptical galaxies as they are in spiral galaxies.

5. The Relationship Between Hot and Cold Gas

Figure 3 shows $L_X/L_B$ versus $L_{100}/L_B$ for nearby elliptical galaxies. The X-ray emission is assumed to come from hot gas and the 100μm emission from cold
Figure 2. CO line fluxes for spiral and elliptical galaxies versus 100 µm flux densities from IRAS. The symbols are as for Figure 1.
dust (although see below). The X-ray luminosities are from the EINSTEIN X-ray data compilation of Fabbiano et al. (1992, FKT), and the 100µm data from Knapp et al. (1989). The data plotted in Figure 3 are for galaxies of morphological type E or E/S0 for which data are given in both catalogues and which are detected at either or both X-ray and infrared wavelengths.

The X-ray emission can arise from the stellar component, from AGNs, and from hot gas. The stellar component was approximated by scaling X-ray to blue light flux for spiral galaxies, also using the data in FKT: 

\[ L_X^{\ast} (\text{erg s}^{-1}) = 1.5 \times 10^{30} \frac{L_B}{L_\odot} \]

(cf. Brown & Bregman 1998) (this includes a factor of 3 for the mass to light difference between the stellar populations of elliptical and spiral galaxies). If the ‘stellar component’ is greater than or equal to the observed X-ray flux, it is taken as an upper limit to the X-ray flux - hence the horizontal line of X-ray upper limits in Figure 3. The infrared luminosities (in erg s\(^{-1}\)) are calculated from 

\[ L_{100} = \nu S_\nu \times 4\pi D^2 \]

using the distances given by FKT.

Figure 3 shown no proportionality between the X-ray and infrared luminosities. The galaxies detected at both X-ray and infrared wavelengths show, if anything, anti-correlation between the fluxes. Two galaxies are obvious exceptions to this, with X-ray detections and 

\[ L_{100}/L_B = \sim 32.15 \]

(Figure 3). These galaxies, NGC 3258 and NGC 3894, have AGNs, and it is likely that AGN emission at significant or dominant levels is also present in some other galaxies plotted in Figure 3.

With the exception of the above two galaxies, those with relatively large values of 

\[ L_{100}/L_B \]

are not detected at X-ray wavelengths, while those with low values are. If the sample is divided at its median 100µm ratio, 

\[ L_{100}/L_B = 31.4 \]

the X-ray detection rate is 80±20% for galaxies with low infrared flux and 30±20% for galaxies with high infrared flux. Despite probable contamination from AGNs, these data show that cold and hot gas are anti-correlated.

A similar result is given by an exhaustive study of the interstellar gas and radio emission from both elliptical and S0 galaxies by Eskridge et al. (1995a,b). Braine & Wiklind (1993) and Braine et al. (1997) find no CO emission to very low limits for X-ray bright elliptical galaxies, both in and out of clusters, in contrast to the CO detection rate in field elliptical galaxies discussed above. Maps of the cold and hot ISM in the bulge-dominated Sa galaxy NGC 1291 by Bregman et al. (1995) find that the cold gas is associated with the disk while the hot gas is associated with the bulge, while an analysis of the hot and cold gas contents of E, S0 and Sa galaxies by Roberts et al. (1991), Bregman et al. (1992) and Hogg et al. (1993) finds the same result. The anti-correlation between hot and cold gas found for elliptical galaxies (which have no disks), however, suggests a more intimate relationship between the hot and cold gas in these systems; the destruction of cold gas by hot interstellar gas, or the cooling of hot gas if enough cold gas is already present.

6. The Distribution of Dust in Elliptical Galaxies: Comparison of Far Infrared Emission and Optical Extinction

Dust is observed in optical images of galaxies because it absorbs and reddens the starlight. The presence of dust lanes and clouds in some elliptical galaxies has long been known (Hawarden et al. 1981; Ebneter et al. 1988), and galaxies with
Figure 3. X-ray versus infrared emission from elliptical galaxies (see text). Filled symbols: galaxies detected at both X-ray and infrared wavelengths. Open triangles: 3σ upper limits for either X-ray or 100µm emission.
prominent dust lanes tend to be HI rich (Morganti, this conference). Systematic optical searches for dust in elliptical galaxies (Goudfrooij & de Jong 1995; van Dokkum & Franx 1996, DF) find dust lanes in the inner regions of a sizable fraction (about 50%) of elliptical galaxies. The analysis of HST archive data by DF is particularly compelling because these elliptical galaxies were selected for observation to be as far as possible dust-free, since the object of the observations was the study of nuclear structure.

The two methods for finding dust clouds and measuring their mass, optical extinction and far-infrared emission, have both advantages and disadvantages. Optical measurements can find small amounts ($\leq 1000 \, M_\odot$) of dust and can measure reddening and hence dust properties, but they are sensitive to geometry: edge-on disks are easy to see, face on disks are not; and the dust cannot be traced much beyond the bright inner (within about $r_e$) regions. Far infrared measurements are unaffected by geometry but have three disadvantages; they are far less sensitive than are optical observations; and since the emission is fairly weak, there are several sources of confusion, as discussed in Section 3, so that the measured dust masses are frequently unreliable. Knapp et al. (1998b) discuss and compare the optical and infrared observations of the DF sample of elliptical galaxies, and find (1) dust is directly detected in about 80% of the galaxies, in good agreement with the DF detection rate corrected for projection effects; (2) the dust masses inferred from the far infrared measurements are almost always much higher than those measured by optical observations (cf. Figure 4; similar results are found by Goudfrooij et al. 1994 and by Bregman et al. 1998); and that the surface densities of dust measured at optical and infrared wavelengths are in remarkably good agreement (Figure 4). (In these figures, NGC 2110 is a galaxy from DF’s sample which is not classified as an elliptical galaxy in any of the conventional catalogues, and is far dustier that any of the other galaxies in the sample).

Thus the ‘typical’ elliptical galaxy appears to contain a small amount of interstellar dust, and by inference cold gas, but it should be noted that neither the optical nor the infrared observations are at all sensitive to dust at large distances from the center of the galaxy, and that many of these galaxies could contain far more interstellar dust than is seen by these observations. The question of whether the extended HI disks or rings seen around many elliptical galaxies contain dust or are primordial thus remains open.

The high resolution optical data discussed by DF were originally acquired to investigate core properties (Lauer et al. 1995). These investigations show that elliptical galaxies fall into two classes - the more luminous have boxy isophotes and cores, while the lower luminosity galaxies have disky isophotes and no cores. Interestingly, the incidence of detectable interstellar dust is essentially identical in these two types of galaxy.

7. Star Formation

Star formation is seen directly in the nearby dusty elliptical galaxy NGC 5128. A small number of low luminosity elliptical galaxies (e.g. NGC 855, NGC 2328, NGC 3928, and NGC 5666) show many of the signs of star formation or even a starburst: blue colors, relatively high dust temperature, in some cases weak
extended non-thermal radio emission, and HII-region like emission spectra. In terms of these tracers, the star formation seems to be behaving just as it does in the disks of spiral galaxies. The remarkable thing that elliptical galaxies have to contribute is the tiny amount of gas that seems to be required to support full-blown star formation. NGC 855, for example, has $4 \times 10^7 \, M_\odot$ of HI and only $\sim 10^6 \, M_\odot$ of H$_2$, the amount found in one Galactic Giant Molecular Cloud; yet it is cheerfully forming stars, as shown by its blue color and emission line spectrum. Young (this conference) finds that the Local Group ellipticals NGC 205 and NGC 185 share this characteristic. Thus star formation seems to be essentially a local process - all it takes is a few thousand $M_\odot$ of molecular gas.

These star formation tracers, if they are present at all, are swamped by other sources of emission in most bright elliptical galaxies, as discussed in Section 1. It is nevertheless highly likely that many other elliptical galaxies support star formation at a low rate - the densities and column densities inferred from CO and infrared observations are high in many cases.

A set of beautiful ISO LWS spectroscopic observations by Malhotra et al. (1998) finds [CII] and [OI] emission from several elliptical galaxies, showing the presence of at least several $\times 10^5 \, M_\odot$ of gas in these galaxies. While these lines, especially the [CII] 158 $\mu$m line, are thought to be important or dominant coolants of the diffuse ISM, ISO and airborne observations of star forming regions show that much of the emission also arises from photo-dissociation regions, and the detection of these lines in elliptical galaxies probably demonstrates the presence of star formation at a low level. Alas, ISO is no more and there is no long-wavelength spectroscopic capability on SIRTF, so it will be a long time before these lines can be probed again in early-type galaxies.
8. The Evolution of the ISM in Elliptical Galaxies

The observations discussed in the previous sections strongly suggest that many elliptical galaxies have a small amount of cold interstellar gas, whose global properties (admixture of gas and dust, molecular and atomic medium, etc.) are not dissimilar to the ISM in spiral galaxies - there is just a lot less of it. This rather strongly suggests that the ‘origin’ of the cold gas in elliptical galaxies is the same as that of spiral galaxies - to wit, the present-day gas content and its composition is the result of continuous evolution: initial star formation is incomplete, stars continue to form, gentle and violent mass loss from stellar evolution enriches the gas and injects dust, and the ISM is partly replenished by mass loss, the infall of (perhaps) primordial gas and gas-containing companions. The ISM, in other words, does not have a single origin any more than that in a spiral galaxy does - it has evolved along with the rest of the galaxy. This point of view suggests that elliptical galaxies have always contained a cold ISM, and that its presence is not an anomaly.

Among the more exciting developments in recent years is the plethora of data on the properties of very distant galaxies. Many of these observations have shown that many elliptical galaxies had much more interstellar gas and star formation in the past than they do now. An investigation of the colors of gravitationally lensed quasars by Malhotra et al. (1997) shows that the lensed objects identified in radio surveys are systematically much redder, by several magnitudes in some cases, than are lensed objects identified in optical surveys, suggesting the presence of several magnitudes of extinction in a large fraction of lenses. Most of the lenses are considered to be elliptical galaxies, as these systems have the mass and central density necessary to produce observable splittings. Thus the typical elliptical galaxy at $z \sim 0.5$ often has a large amount of dust in its inner regions. A range of epochs for star formation may be inferred from color magnitude diagrams and other studies which find differences in the stellar populations among galaxies - for example, the recent study by Pahre et al. (1998) which shows that the slope of the elliptical galaxy sequence (the fundamental plane) depends on the photometric band in which the measurement is made, illustrating the difference in stellar content along the sequence.

How are these results related to the present-day cold gas content of galaxies? Suppose that the star formation of a galaxy is simply proportional to the mass $M_g$ of cold interstellar matter. The rate at which the ISM is consumed is then

$$dM_g = -fM_g \, dt$$

where $f$ is the fraction of the gas used up per unit time ($dM_g$ is about 0.7 - 0.8 times the total star formation rate, because a fraction of the gas is returned by stellar evolution). If the initial mass of the galaxy is $M_o$, then today ($t_o$)

$$\frac{M_g}{M_o} = \frac{M_g}{M_g + M_*} = e^{-f_{t_o}}$$

The observations discussed above show that elliptical galaxies typically have $M_g/L_B = 0.002 \rightarrow 0.2 \, M_\odot/L_\odot$. Taking a typical stellar mass to blue light ratio for these galaxies of $3 \, M_\odot/L_\odot$ gives a median present day value of $M_g/M_o$
of about 0.004 for an $L_\star$ galaxy, corresponding to $f = 10^{-9}$ yr$^{-1}$. The same calculation for a spiral galaxy gives $f = 2 \times 10^{-10}$ yr$^{-1}$. These numbers correspond to a present star formation rate of $1 - 3$ M$_\odot$ yr$^{-1}$ in spiral galaxies and $M_g/M_\odot = 0.5$ at $z = 2 - 3$ for an $L_\star$ elliptical galaxy.

Elliptical galaxies are similar to spiral galaxies, in other words, in that they seem to have an evolving interstellar medium; the difference is that the timescale for star formation is much shorter. Franceschini et al. (1998) find indications that the star formation timescale is shorter for galaxies of larger mass. Could the ‘second parameter’ which determines the star formation rate be the velocity dispersion of the galaxy or galaxy subcomponent?

Thus the origin of the gas in elliptical galaxies may be no different from that in spiral galaxies, i.e. a combination of intrinsic gas, stellar mass loss and infall. This seems not to be the case for elliptical galaxies in clusters; these galaxies contain a lot of hot gas but are almost devoid of cold gas. The fraction of ‘peculiar’ elliptical galaxies in the Revised Shapley-Ames Catalogue (Sandage and Tammann 1981) goes from about 5% in clusters to almost 50% in the field. Perhaps the epithet ‘peculiar’ has been attached to the wrong galaxies; it looks as though galaxies in the field, both spirals and ellipticals, usually contain some coeval cold gas but that galaxies in clusters, both ellipticals and (former) spirals, do not. Elliptical galaxies in clusters may be no more typical than are spiral galaxies in clusters.

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Discussion

E. Brinks: I like your suggestion that one should consider the peculiar Es in the field as being actually the normal E population and that the Es in clusters have been stripped of their ISM. But as Es have quite a deep potential well, how can you strip them, and in such an efficient way?

G. Knapp: Perhaps its better to say that the cold gas in elliptical galaxies in clusters is heated by the same processes as heat the intergalactic gas.

R. Bower: The fraction of the baryons which are in stars in clusters of galaxies is only about 10%. So I agree with the suggestion by Cen and Ostriker that a similar fraction holds for the field galaxies.

C. Baugh: The Cen & Ostriker argument inferring the global density of stars at $z = 3$ from observations of Lyman-break galaxies is weak - the Lyman-break galaxies sample only a small range of the full luminosity function at this redshift - a lot more star formation could be going on in smaller systems. Also, corrections
to the star formation rate for obscuration by dust could be as much as a factor of 2-5.

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