Abstract

Infrared emission has been detected from normal elliptical galaxies and from clusters of galaxies at 60$\mu$m and 100$\mu$m with the IRAS satellite. In both cases, the emission has the characteristics of cool dust with a temperature near 30K. For the elliptical galaxies, there is a correlation between the optical luminosities and the far infrared luminosities. The likely source of the dust in these systems is mass loss from stars, which is heated by starlight and either is distributed throughout the galaxy or falls into a central disk. Analysis of upcoming ISO data will permit us to distinguish between these possibilities.

The far infrared emission from clusters of galaxies is of high luminosity but is only detected in 10% of the cases. The heating is either due to electron impact from the hot gas (a suitable explanation for one cluster) or photon absorption. The source of the dust is probably gas stripped from galaxies. For clusters, ISO data will provide good mass determinations and positions, thereby allowing us to determine the source of the heating.

1 Introduction

Prior to the launch of the Infrared Astronomical Satellite (IRAS), there were a variety of astronomical objects that were anticipated to be sources of far infrared emission, such as gas-rich spiral galaxies and Galactic star-forming regions. Early-type galaxies and clusters of galaxies were not among the objects that were expected to be detected with IRAS. Early-type galaxies have very little detectable cold gas from 21 cm studies and are dominated by their hot X-ray emitting atmospheres [16], while clusters of galaxies have vastly more substantial amounts of even hotter gas [7]; in these environments, dust would not survive long against sputtering by the hot gas nuclei. Therefore, it came as a surprise when far infrared emission was detected from these systems.
In elliptical galaxies without active galactic nuclei (AGN), the FIR emission indicates the presence of gas and dust shed during normal stellar evolution, or perhaps captured during a merger event with a dwarf irregular. In clusters of galaxies without AGN, the FIR emission is most likely due to gas and dust that has been stripped from spiral galaxies in the cluster, possibly in catastrophic fashion. The study of FIR emission in these two different situations can broaden our understanding of these different systems. Here we describe the present situation as determined from IRAS data and discuss the likely gains that data obtained with the Infrared Space Observatory (ISO) will provide.

2 Far Infrared Emission From E and E/S0 Galaxies

While early type galaxies have the same fraction of mass in gas as spiral galaxies, the composition of their interstellar medium is strikingly different. Most of the the gas in early-type galaxies is hot (10^6K - 10^7K) X-ray emitting material, and only a small amount is in a cool phase. It is this cool phase that will be of concern in this talk because it can be particularly revealing about the nature and evolution of these galaxies and their stellar systems.

Cold material can be built-up in early-type galaxies either through the capture of external gas or by accumulated stellar mass loss. In the former case, a dwarf galaxy may collide with the larger elliptical so that its cold gas becomes part of the galaxy immediately. Alternatively, a dwarf galaxy may pass through the hot atmosphere of the early-type galaxy (or that of a group or cluster in which it resides) and have its cold material stripped away; eventually this material falls into the elliptical, as appears to be the case for a dwarf galaxy UGC 7636 near NGC 4472 [13]. In such cases, the orbit of the captured gas often will not be rotating in the same direction as the galaxy and the axis of rotation may not be aligned with minor axis of the elliptical. In these cases, some gas can be identified as being captured, through careful 21 cm mapping. If a considerable amount of gas is captured (e.g., 10^9 M⊙), these dramatic events may reshape the nature of the galaxy, leading to a disk of stars in addition to the spheroid.

A constant source of cold gas for elliptical galaxies is the mass lost from stars, which accounts for 0.1-1 M⊙/yr in moderately bright elliptical galaxies. The fate of this cold gas is not entirely clear because the interaction with the hot atmosphere has not been extensively studied. Most of the mass loss occurs during a brief evolutionary period near the red giant and planetary nebular phase of low mass stars (e.g., main sequence masses of 0.8-1.0 M⊙). The mass shed from the star interacts with the hot atmosphere of the galaxy and is expected to be brought to rest by shocks; in the process, the shocks heat the gas to the temperature of the hot galactic ISM. The first detailed calculations of this complicated process are now being carried out [14]. These calculations indicate that a bow shock around the star leads to a shock in the stellar mass loss that pushes the material downstream but does not lead to a great deal of heating. As this wake drifts downstream, there is a substantial velocity differential with the hot atmosphere, so Kelvin-Helmholtz instabilities cause fingers of material to be drawn out of the wake. The mass in these fingers of material is heated by shocks and mixing, while cooling occurs through optically thin radiative losses. When the mass loss has its origin from a star that has a velocity significantly less than the velocity dispersion of the galaxy, the shock heating is reduced and radiative losses are enhanced due to the tendency of material to seek pressure equilibrium. The calculations, now in progress, will determine the fraction of mass lost from stars that remains cold and that which is converted into hot gas.

Stellar mass loss that remains cold will sink toward the center of the galaxy, and if it retains the net angular momentum of the stellar system, it will settle into a small disk. The size of the disk depends on where the gas was lost and the rotational velocity of the system, but
the characteristic size would be 1/4 - 1/30 the optical size of the stellar system. The mass of the disk of cold gas and dust would depend upon the rate at which the cold material is converted into stars and the fraction of the stellar mass loss that remains cold. Provided that the hot gas does not eventually evaporate the cold material, the dust in this cold gas can be long-lived because it is "protected" against sputtering by the hot gas.

For the stellar mass loss that is heated to hot gas temperatures, the fate of the dust is different. The dust finds itself in a hot environment and its drift time into the center of the galaxy is long, so the dust interacts with the hot gas and photons locally, until it is destroyed by sputtering. The sputtering time is approximately (e.g., [8])

\[ 7 \times 10^7 \left( \frac{n_e}{3 \times 10^{-3} \text{cm}^{-3}} \right)^{-1} \left( \frac{a}{0.1 \mu m} \right) \text{yr} \] (1)

where \( n_e \) is the electron density of the hot gas and \( a \) is the grain size. Sputtering is largely due to the protons and alpha particles colliding with the grains, while electron collisions lead to heating of the dust grains. Ultraviolet and near-ultraviolet photons from elliptical galaxies are another, probably more significant source of heating of the dust [15], [19].

The dust that is mixed into the hot gas will be distributed on a scale as large as the galaxy while the material that falls into the center of the galaxy will be relatively compact. Which of these components dominates the emission depends upon two factors: the rate of star formation in the disk and the fraction of gas that remains cold and falls into the disk. This latter quantity can be calculated [14], and it may be possible to gain information about the star formation rate through studies of the young stellar component (e.g., [20]). The dust properties can be studied directly from their thermal emission, which has been possible through IRAS observations, and instruments on ISO offer the possibility of much more detailed studies. I will try to summarize the state of the IRAS observations and indicate the potential of observations being obtained with ISO.

The IRAS satellite had four broad photometric bands centered at 12\( \mu m \), 25\( \mu m \), 60\( \mu m \), and 100\( \mu m \), with the latter two being the most sensitive to the thermal emission from dust mixed with cold gas in ordinary spiral galaxies. Given the sensitivity of IRAS and the sensitivity of radio telescopes that detect neutral hydrogen 21 cm emission and CO(1-0) 115 GHz emission, IRAS was capable of detecting the presence of cold material that is below the detection threshold of the radio telescopes (for typical dust to gas ratios in near-solar abundance gas). Consequently it was able to perform more sensitive searches for cold dust and gas in a variety of astronomical objects.

One class of astronomical object studied in this manner were early-type galaxies, where early studies indicated that the detection rate approached 50% [11], [12], [10]. This was a very exciting result as it indicated that dust was extremely common in systems where cold gas was thought to be rare. A particularly surprising result was that there was no clear correlation between the apparent B magnitude and the FIR flux. This would suggest that the intrinsic dispersion between the optical and far infrared luminosities was quite large, another potentially important result.

As often occurs in detection studies, the significance of the FIR emission in many of the galaxies was near the detection threshold, and we have learned considerably more about low signal-to-noise measurements since these initial studies on the subject (see below). The IRAS detection software provides a flux, uncertainty, and position; at moderate or high S/N levels, these quantities are known to be accurate. However, at low S/N, the noise appears to be non-Gaussian in nature, and studies of blank fields show that the spurious detection rate for sources near 3 sigma is 16% at 60\( \mu m \) and 31% at 100\( \mu m \) [6]. This work indicates that sources above the 98% confidence threshold have S/N (from the standard SCANPI IRAS package) of 4 in the
60\(\mu\)m filter and 4.5 at 100\(\mu\)m. The remainder of the study focuses on the 60\(\mu\)m and 100\(\mu\)m flux and the "bolometric" flux that is often formed from these two quantities:

\[
F_{\text{FIR}} = 1.257 \times 10^{-11} (2.58F_{60} + F_{100})
\]

where the 60\(\mu\)m and 100\(\mu\)m fluxes are in Janskys.

Given the above criteria for detection accuracy, we have reconsidered the rate of detection of early-type galaxies [2]. The approach used here is different than that of Knapp [12], which was a comprehensive survey that was intended to include all early-type galaxies, including those that had nuclear activity. Here we are asking whether normal non-interacting, non-peculiar early-type galaxies contain cold material. In doing so, we begin with all of the E and E/S0 galaxies in the RSA catalog that are not listed as peculiar, do not possess nuclear activity, are not near contaminating sources (e.g., spiral galaxies), and do not lie in regions of rapidly changing Galactic cirrus emission. After excluding these sources, we find that 15 galaxies are detected above the 98% confidence level (12% of the sample) and an additional 7 galaxies are detected in the 90-98% confidence range (5% of the sample). This is a lower detection rate than found previously, but we do not mean to imply that previous works are wrong; the selection criteria imposed here are different and quite strict. Rather, the purpose of this work is to determine a sample of "near-certain" detections to investigate whether these galaxies show a connection with other galaxy properties.

First, we compare the bolometric FIR flux to the optical B band flux and we find a positive correlation, which indicates that optically bright objects are also brighter in the infrared. Since we are only detecting the highest \(F_{\text{FIR}}\) objects, this study only defines the upper envelope of the optical to FIR relationship, where we find that \(F_{\text{FIR}} \propto F_B^{0.24 \pm 0.08}\). It is not particularly surprising that such a correlation exists, although it is relatively flat. A positive correlation also exists between the FIR and blue luminosities, with \(L_{\text{FIR}} \propto L_B^{1.65 \pm 0.28}\). The temperature of the dust is in the range 23-38 K, with a median of 30K; the dust temperature is uncorrelated with \(L_{\text{FIR}}\).

We have examined whether there are other signs of cold gas in these FIR-detected galaxies and find that an unusually high fraction possess other forms of cold or cool gas. Of the sample of 15 excellent FIR detections, four are detected in HI or CO, whereas only one detection was expected if these galaxies were representative of the E and E/S0 galaxies in the RSA catalog [16]. Also, several of these galaxies have not been observed at 21 cm or have very poor upper limits, so there are only a few galaxies with stringent upper limits to their HI and CO content. Since less cold gas is required for a galaxy to be detected in the FIR than at 21 cm or in CO, the presence of FIR emission without HI or CO emission is not inconsistent. Similarly, a larger fraction of these FIR galaxies have optical emission line gas; 78% were detected in \(H\alpha\), whereas only 29% would be expected to show such lines in a randomly selected sample.

With this set of detections from non-AGN early-type galaxies, we can investigate whether the dust is located in a central disk or distributed throughout the galaxy. This issue can be addressed by complementary observations as well as by comparing models to the data. Observationally, Goudfrooij [10] has obtained dust masses from extinction that can be compared to the dust masses inferred from the FIR observations. The extinction dust mass is usually an order of magnitude smaller than the FIR dust mass (in our sample and also in Goudfrooij’s sample), which can be explained if most of the dust is spatially distributed so that it does not create distinct dust lanes. Given the uncertainties in determining dust masses from extinction observations and from FIR observations, we regard this as a tantalizing suggestion of distributed dust rather than definitive evidence; it is interesting to note that most changes in our assumptions, such as the addition of cool dust, would increase the dust mass, indicating the existence of more distributed dust.
The most detailed models yet developed are those by Tsai and Mathews [18], [19], in which the dust from the stars is mixed with the hot gas where it is slowly destroyed by sputtering while it is heated mainly by starlight. Most of their models predict a luminosity that is too low and an effective dust temperature ($F_{60\mu m}$ to $F_{100\mu m}$ ratio) that is too high relative to the data. However, for the model where their maximum grain size is increased to 0.9 $\mu$m, the $F_{60\mu m}$ to $F_{100\mu m}$ ratio is similar to that observed, and the predicted infrared luminosity ($log(L_{FIR}) = 42.66$) is comparable to that observed for most galaxies. The galaxy with the highest $L_{FIR}$ is NGC 7196, which is 6 times more luminous than the Tsai and Mathews predictions, and this is the only galaxy with CO emission. It is likely that this galaxy has a central disk where most of the cold material resides. Without further detailed studies, it is difficult to determine how many of the galaxies are dominated by central cold disks, but for most galaxies, the models can be explained with the infrared luminosity being produced by distributed emission (e.g., mass loss from stars distributed throughout the galaxy).

In summary, one of the challenges in understanding the cold interstellar medium in elliptical galaxies is to separate galaxies dominated by captured gas from those where the gas is generated internally. We have concentrated on galaxies where the cold gas content has the greatest likelihood of being generated internally by selecting non-peculiar E and E/S0 galaxies. The IRAS emission is clearly detected in a modest fraction (12%) of the galaxies and there is a correlation between the FIR flux and optical flux, as well as between the FIR and optical luminosities. For most of the galaxies, the FIR emission is consistent with distributed emission, as would be expected if we are detecting the emission of mass loss from stars and the mass loss is distributed through the galaxy. ISO holds the possibility of determining directly whether or not the dust is distributed throughout the galaxy. ISOPHOT has adequate resolution to map the shape of the emission in the nearest elliptical galaxies at 60 $\mu$m-180 $\mu$m while ISOCAM can study the polycyclic aromatic hydrocarbon (PAH) emission on angular scales of several arcseconds. The data are now being accumulated and analyzed and the results emerging in the next few years should be very exciting.

3 Far Infrared Emission From Clusters of Galaxies

The original motivation in searching for infrared emission from clusters of galaxies grew out of issues surrounding cooling flows in clusters. The logic was that if gas is cooling at a rate of 100 M$\odot$/yr and forming into stars at the same rate, that the star formation process may be accompanied by dust and infrared emission. If the infrared signature were scaled from spiral galaxies by the star formation rate, the emission would be visible. The star formation rate in typical spiral galaxies is a few solar masses per year, so a cooling flow cluster would be about 30 times more luminous in the FIR than an ordinary spiral galaxy. Furthermore, the emission would be expected from the cluster center where spiral galaxies are rare and where the weakly emitting ellipticals would be undetectable at the distances of most Abell clusters, so contaminating emission from galaxies would not occur. Thus, the interpretation of an infrared signature, should one be present, would be straightforward.

Two efforts searched for such emission in rich clusters, primarily utilizing Abell clusters at moderate redshifts ($z = 0.02-0.2$) and with strong known X-ray emission. These investigators (3,9) reported that about 18-46% of their samples of a few dozen clusters showed 60$\mu$m or/and 100$\mu$m emission above the 3$\sigma$ level; nearly all of the detections were between the 3$\sigma$ and 5$\sigma$ level. There was no apparent correlation between the FIR properties and the X-ray or optical properties of the clusters. The ”detections” did not appear very convincing to the eye, so we began a new and more thorough effort to understand the noise properties and to enlarge
the cluster sample size so that statistical studies would become possible.

It is worth trying to understand what goes into the detection of an IRAS source to understand the noise properties and contamination issues. IRAS was usually used in scanning mode whereby rectangular detectors swept over a single point many times, usually with similar position angles. At \( 60 \mu m \) and \( 100 \mu m \), the detector width is about 4.5' (by 1'), so the location information for weak sources is generally quite poor, especially perpendicular to the scan line. Also, in crowded fields, the width of the detector makes it quite easy for contamination to occur from more strongly emitting sources, such as a foreground spiral galaxy near the intended target.

However, perhaps the greatest problem with detecting sources is in quantifying the statistical properties of the "baseline". That is, it was hoped that as IRAS scanned across sources, one would see "baseline" emission fluctuate about some low value with a Gaussian distribution, with the source visible in clear contrast. The fluctuations are a combination of the Galactic Cirrus emission and the detector noise. Unfortunately, we find that the fluctuations do not appear to have a normal distribution, and this has profound effects on the detection of weak sources \[\text{6}\]. We selected about 200 blank fields and extracted a flux in the usual fashion, using SCANPI (originally, the IRAS data product ADDSCAN). We plotted a distribution of the extracted "signals" and found it to be much broader than a Gaussian distribution. We found that 16% of the locations at \( 60 \mu m \) and 31% at \( 100 \mu m \) had positive signals at or above \( 3 \sigma \). A simple criteria for the true confidence as a function of SCANPI S/N was derived, and it was found that for 98% confidence detections, one should use \( 4 \sigma \) at \( 60 \mu m \) and \( 4.5 \sigma \) at \( 100 \mu m \). Note that 98% confidence would correspond to \( +2 \sigma \) in Gaussian statistics. The IPAC Faint Source Catalog is above these criteria and does not suffer from a substantial number of spurious detections.

The sample of clusters used for this study included all of the Abell clusters with a dominant central galaxy (Bautz-Morgan class of I or I-II; \[\text{1}\]) plus a few clusters with moderately high X-ray luminosities. This led to 158 clusters for which IRAS data were available with a mean redshift of 0.076, and which forms a complete sample to a redshift of about 0.2. We found that 10% of the sample was detected above the 98% confidence limit (18 clusters), which is significantly lower than previous studies. The higher detection rates of previous studies is partly due to spurious detections near the \( 3 \sigma \) level, but another factor is that the samples were chosen differently and the mean distances were often different (e.g., the mean redshift was only 0.043 for the sample of Bregman, McNamara, and O’Connell \[\text{3}\]).

The spectrum of most detected clusters, as defined by their \( 60 \mu m \) and \( 100 \mu m \) fluxes and upper limits at \( 12 \mu m \) and \( 25 \mu m \), is similar to that expected from cool dust and easily distinguished from starburst galaxies and AGNs. This indicates that we are usually detecting emission from warm dust with a typical temperature in the range 24-33 K. No correlation was found with cluster properties, although the detected clusters are slightly closer than the sample as a whole.

Some of the scientific issues that are raised by this discovery are the source of the dust and the origin of the heating for the dust. The latter issue is particularly acute because of the large FIR luminosities. A typical FIR luminosity is \( 10^{44.5} \text{erg/sec} \), which is an order of magnitude larger than the X-ray emission from within the core (cooling flow region; \( r = 100 \text{kpc} \)) and is comparable to the total X-ray luminosity of the cluster. The FIR luminosity is typically a factor of 5 smaller than the bolometric optical emission from the central dominant galaxy. Given these relative luminosities, if the energy source is electron collisions by the hot gas, then the cooling rate for the X-ray gas is an order of magnitude greater than is usually assumed (e.g., the cooling rate is closer to \( 1000 \text{M}_\odot/\text{yr} \) rather than \( 100 \text{M}_\odot/\text{yr} \)). Since only 10% of clusters are detected, the duty cycle of this intense cooling may be relatively brief. If photons heat the dust and the dust is superimposed upon the central dominant galaxy, substantial reddening
would be present. Reddening toward these central galaxies has been searched for, but it is rarely detected and never at the level needed to power the dust. This does not rule out photon heating since the dust could be offset from the central galaxy, given the poor IRAS resolution. We note that in the nearby Centaurus cluster, dust emission and extinction is observed in NGC 4696 [17], but our clusters tend to be much more distant and the energy considerations are more severe.

Heating by fast electrons makes predictions about the density of the hot gas, and it is possible to test these predictions through the use of X-ray imaging data to determine the electron density in a given cluster. The rate of electron collisions must be adequate to raise the dust temperature to the level implied by the FIR data. ROSAT data was used to check this for 5 clusters detected with IRAS. We found that in Abell 1991, the electron density is above the value needed to power the dust emission, but that for four other clusters (Abell 1541, Abell 1691, Abell 2199 and Abell 2634), the electron density is too low by a substantial amount [4] [5].

The dust mass is \(10^7 - 10^8\) M\(\odot\), so the associated amount of gas is \(10^9 - 10^{10}\) M\(\odot\), which is a typical mass for the interstellar medium of a galaxy. It is possible that as a galaxy passed through the core of the cluster, gas and dust were stripped out and are now radiating. The sputtering time is short for dust in this environment, typically \(10^8\) yr in the cluster core \((n_e = 3 \times 10^{-3}\) cm\(^{-3}\), dust radius of 0.2 \(\mu\)m\)), so events like this would need to be common unless the dust were protected by being embedded in cooler gas.

It is hoped that ISO will be able to answer two of the primary issues in this area: the location of the dust and the dust mass. The IRAS data showed us that there is dust emission somewhere within a 1' \(\times\) 4.5' box, but ISO will be able to locate the emission to a fraction of an arcminute, which should tell us if the dust is indeed cospatial with the dominant galaxy. ISOPHOT maps of clusters detected with IRAS are being obtained for this project, and other teams have ISOCAM data of clusters, which will be valuable if there is significant PAH emission from the dust. IRAS also allowed us to estimate the mass of dust, but it simply placed a lower limit on the dust mass since IRAS was not particularly sensitive to low temperature dust. ISOPHOT has the capability to detect low temperature dust due to spectral windows that extend to longer wavelengths than IRAS; we have utilized ISOPHOT’s 180 \(\mu\)m filter in our raster scans. Although it is too early to report our results, clusters have been detected by ISOPHOT and we hope that improved data processing will lead to several interesting results.

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