Chapter 1

Introduction

1.1 Dark regions of the sky

The presence of dark regions in the stellar fields of the Milky Way was first noted by William Herschel, who referred to them as “vacancies”. These starless regions of the sky were not of particular interest for the great astronomer, except for their close association with bright nebulæ often found in their proximity. Well aware of this connection, he was used to call for his sister Caroline each time one of these empty regions was sweeping into the field of view of his telescope, to record the new patches of luminosity that were expected to follow.[1]

But it wasn’t until Edward Emerson Barnard, in 1889, started to take pictures of the Milky Way, that a photographic record of Herschel’s vacancies was available for scientific study. In 1919 he first published a catalogue of 182 “dark markings”, based on observations made with a telescope he built himself, using a 6 inches photographic lens bought second hand in San Francisco. Intrigued by the presence of these black empty patches of sky in regions otherwise bright of starlight, he was among the first to suspect their true nature: not just a coincidence in the distribution of stars, but the consequence of some dark opaque medium absorbing the background stellar radiation.

It is now well known that Herschel “vacancies” and Barnard “dark markings” were obscuring clouds of dust and gas, but it took more than 30 years since their photographic discovery, for this explanation to be widely accepted. As early as 1926, thanks to the counts of “extragalactic nebulæ”

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[1] See the excellent narration in “The Dust of Space” by Seares (1940).

FIG. 1.1.— The Horsehead Nebula, object No. 33 in Barnard's catalogue, is a typical example of thick dust lane obscuring a background bright nebula and stellar field. Barnard thought of it as one of the most convincing cases for the existence of a dark absorbing medium in the galaxy: "*clearly a dark body projected against, and breaking the continuity of, the brighter nebulosity*" (Barnard, 1913). Digital image from NOAO.

(galaxies) by Edwin Hubble[2], it was recognized the presence of a diffuse absorbing stratus (less opaque than Barnard's dark nebulæ), symmetrically placed along the galactic plane. Extinction measurements based on similar techniques (Trumpler, 1940) were finally able to determine the amount of obscuration, leading to the conclusion that the interstellar medium (ISM) was filled with tenuous amounts of fine solid particles. The selective absorption of light by these particles was found to cause a measurable "reddening" in the spectra of background stars, similar in nature to the red tint of the sunset radiation, given by the dust particles suspended in the Earth atmosphere.

The composition and origin of the interstellar dust grains was identified twenty years later, in a fundamental work by Hoyle & Wickramasinghe (1969). By comparing the wavelength dependence of interstellar extinction with the absorption index of various laboratory materials, they were able to conclude that "[. . .] *interstellar grains may be a mixture of graphite particles formed in carbon stars and of silicates in oxygen-rich giants*"[3].

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[2] See Hubble (1926) and the more extensive survey in Hubble (1934)

[3] Hoyle & Wickramasinghe (1969)

After the turn of the century, their basic assumptions are still valid, and the advances of the observational techniques covering the whole electromagnetic spectrum, together with the availability of new theoretical and laboratory opacities, have shown the presence of dust in a rich mineralogic variety, and in many different astrophysical contexts. The aim of this work is to analyze the observations of astrophysical dust in the mid-IR region (5–20 μm), where its thermal radiation is emitted. This thesis focuses on the two extremes in the life cycle of cosmic dust grains: its formation around cool giants in late evolutionary stages, and the possibility of its survival (and ultimately its destruction) in the hostile spaces between the galaxies.

In the next section the conditions of dust grains in these environments are briefly described. The following chapter introduces the theoretical basis of the interactions between dust, radiation and matter, which take place in the circumstellar and intergalactic environments.

Basic tools for the mid-IR analysis of circumstellar dust are then introduced in chapter 3. Chapter 4 shows an application of these techniques, making use of radiative transfer modeling in order to study the mass loss processes of variable stars in the Asymptotic Giant Branch (AGB) phase.

Chapter 5 describes a succesful project of direct mid-IR imaging of circumstellar dust, around AGB sources modeled in the previous chapter, and along a molecular outflow in a Young Stellar Object (YSO). The observations are analyzed and compared with the theoretical predictions, in order to test their recent mass loss history and geometry.

In chapter 6, the chances to observe the emissions of dust surviving at the center of cluster of galaxies (IntraCluster Medium, or ICM) are finally evaluated, and some applications are proposed.

1.2 Dust grains in the galaxy and beyond

Since the existence of a dark diffuse medium able to absorb the stellar radiation in the ISM was first recognized, the presence of dust has been discovered in a multitude of different environments. In this section the dust metamorphosis in the Galaxy is briefly described, by discussing with particular emphasis the properties of dust in the ISM, around giant stars (where it is formed) and in the intergalactic medium (where it is finally destroyed).

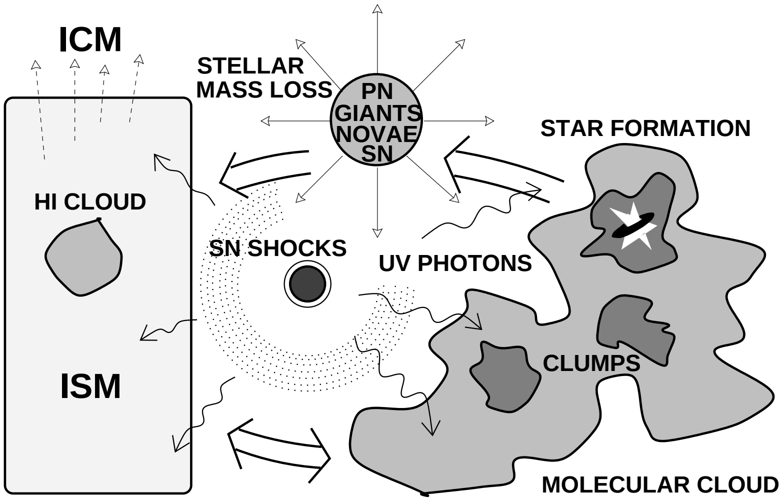

FIG. 1.2.— Creation and destruction cycles of dust in the Galaxy. Adapted from Tielens (1989).

1.2.1 Dust metamorphosis in the galaxy

Dust is a fundamental constituent of the Galaxy, and plays a major role in its evolution. Dust grains created around giant stars drifts into the diffuse interstellar medium, where they are eroded by the hot component of the ISM and the energetic UV background. Part of this dust, however, is eventually accumulated in dense molecular clouds, where it is protected from the more energetic photons, and finds a favorable environment for its survival and growth. Here, far-infrared radiation emitted by dust removes the gravitational energy of collapsing molecular clouds, thus allowing for star formation to occur. In these processes dust becomes part of protostellar disks, feeding the young stars with metals, and ultimately providing the building material for planetary systems. Some of the ISM dust, finally, is assumed to became part of the intergalactic medium, blown away from the galactic plane by the action of strong galactic winds (Matteucci & Gibson, 1995), or by means of ram pressure stripping as the host galaxy crosses the denser central regions of the ICM (Gunn & Gott, 1972).

This complex interplay between processes of formation, destruction, and growth of galactic dust, summarized in figure 1.2, is crucial for the chemical evolution of the Galaxy, and the chemical enrichment of the extragalactic medium.[4]

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[4] See, e.g. the review in Dorschner & Henning (1995).

The term *stardust* coined by Ney (1977) is well justified by the fact that the main source of cosmic dust is the stellar mass loss. The formation of small grains in dense molecular clouds and the growth of refractory dust in the diffuse ISM, however, have recently turned out to be processes of at least comparable importance. To these well recognized dust sources, one may add the possibility of dust formation in *cooling flows* at the core of clusters of galaxies (Fabian et al., 1994), even though this idea is quite controversial. The fact that cosmic dust grains originates and are reprocessed in many different environments is well reflected by the large variety of mineralogical composition and grain sizes encountered in the galactic and extragalactic dust.

The destruction of dust, on the other end, is mainly due to the interactions with energetic UV photons and SuperNova Remnants (SNRs) shocks in the ISM, and to sputtering by hot plasma and the X background radiation in the ICM. The physics of these interactions in the interstellar, circumstellar and ICM environment is briefly discussed in the following sections.

1.2.2 Interstellar dust

Dust in the ISM is subjected to many chemical and physical processes, including grain-grain collisions, erosion by sputtering, irradiation effects and grain growth due to recondensation of evaporated and sputtered grain material.

Grain growth in the ISM is necessary to maintain the observed interstellar dust density, due to the high depletion rate by the hotter surrounding medium. The lifetime of ISM dust is estimated to be $\sim 4 \cdot 10^8$ yr for carbonaceous grains, and $\sim 2 \cdot 10^8$ yr for silicate material (Jones et al., 1994). The timescale for ISM dust replenishment by stellar mass loss is, however, ten times larger ($2.5 \cdot 10^9$ yr, see e.g. Jones & Tielens 1994), and is thus insufficient to keep the balance.

Two mechanisms are invoked to solve this deficiency: formation of small grains and Polycyclic Aromatic Hydrocarbons (PAH) triggered by Supernova (SNs) shocks and C^+ ion chemistry (probably responsible for the interstellar gas heavy metal depletion), and migration of ISM dust in molecular clouds, where it is protected from the more energetic radiation and finds more favorable conditions for grain growth. By comparing the lifetime of dust in the diffuse ISM with the fraction of the ISM that is part of molecular clouds (about 30%), and the molecular clouds lifetimes ($\sim 10^8$ yr), one can assume that each ISM dust particle will be processed in a cloud for more than 10 times during its mean lifetime (Mathis, 1990). While in the clouds, dust grains undergo chemical processing that modify their size distribution, leading to the formation of larger grains coated with ice mantles.

The grain size distribution and chemical composition of dust in the diffuse ISM and in clouds is thus different. From the fitting of the observed galactic extinction curve, Mathis, Rumpl & Nordsieck (1977) derived a power-law for the diffuse ISM grain size distribution ("standard" MRN distribution):

$$n_d(a) \propto a^{-k} \qquad \text{for} \quad a_{min} \lesssim a \lesssim a_{max} \tag{1.1}$$

where $k \sim 3.5$, $a_{min} \sim 0.005$ μm and $a_{max} \sim 0.25$ μm. Further analysis by Kim, Martin & Hendry (1994) using a larger number of observational constraints, found deviations from the MRN distribution required to explain the UV extinction curve, and an exponential cutoff for $a \gtrsim 0.2$ μm, that allows a better fitting of the dust far-infrared radiation:

$$n_d(a) \propto a^{-k} e^{-a/a_o} \tag{1.2}$$

with $k \sim 3.06$ for silicates and $k \sim 3.48$ for graphite. The details of the deviations from the simple MRN distribution and the position and slope of the exponential cutoff are different between diffuse ISM and dust in molecular clouds, and result in a relative decrease of small particles in the clouds, accompanied by the presence of larger grains.

As already shown, extinction measurements are the main source to determine the composition of ISM dust. Emission is also important, however, because it probes the composition of the most extincted regions, opaque at optical wavelengths, and allows the determination of the less abundant components. The dust thermal emission, in fact, amounts to about the 30% of the total luminosity of the Galaxy, mainly at far infrared wavelengths. Strong Unidentified Infrared Bands (UIB), have also been observed in the 3.3 – 11.3 μm range, and their interpretation is a strong constraint on the proposed models of ISM detailed composition.

The current accepted models of the diffuse ISM assume a mixture of refractory grains, mainly carbonaceous and oxidic. Among the C-based material, the main components are graphite, Hydrogenated Amorphous Carbon (HAC) and PAH, with this last ingredient introduced to explain the observed UIB. The oxidic part of the ISM dust is in turn made of amorphous (Mg-dominated) silicates and Mg-Fe oxides. Apart from these main chemical components, minor species are also found, as e.g. sulfides grains (Begemann et al., 1994). SiC is also expected, due to its high rate of production in C

TABLE 1.1 TOTAL GALACTIC STELLAR MASS LOSS.

Source	Total $\dot{M}$ $M_\odot$ yr^{-1}	fraction %
Thermally pulsing AGB stars	$5.5 \cdot 10^{-1}$	73
Supernovæ	$7.5 \cdot 10^{-2}$	10
RGB stars	$5.5 \cdot 10^{-2}$	7
Wolf Rayet stars	$2.5 \cdot 10^{-2}$	3
Red and Yellow Supergiant stars	$2.0 \cdot 10^{-2}$	3
Early AGB stars	$2.0 \cdot 10^{-2}$	2.5
Main Sequence stars	$1.0 \cdot 10^{-2}$	1.5

Adapted from Sedlmayr (1994)

stars, but is probably not abundant, as inferred by the absence of interstellar absorption at 11.3 μm, where its main feature is located.

1.2.3 Circumstellar dust

High luminosity giant stars are the main stellar source of dust, since they provide up to 90% of the total stellar mass loss. Stars in the AGB and the post-AGB, in particular, account for the greater part of the total yield, as shown in table 1.1.

Supernovæ (SN) are also important, being the main contributors of elements heavier than carbon, and thus playing a major role in providing refractory grains to the ISM. Their total yield, however, is not well known, due to the uncertainties in their dust production efficiencies, and because it is difficult to estimate the grain survival rate after the SN explosion. Wolf Rayet stars (WR), Red Giants Branch stars (RGB) and Main Sequence stars (MS) are instead secondary contributors.

The initial evidences for a circumstellar origin of dust came from the reddened spectra of the parent stars, which show various degrees of extinction at optical wavelengths (first suggested by Loreta 1934), and strong mid-IR infrared excess. A better understanding of the circumstellar dust composition came with the development of infrared spectroscopy. At the end of the 1960s, it was confirmed the assumption that stars with M spectral type were forming silicate particles, while carbon stars were the sources of carbonaceous grains.

With the IRAS satellite mission, a database of 5,425 Low Resolution Spectra (LRS, 1986) was collected in the 7.7–22.6 μm range. Since most of the observed sources were AGB, post-AGB and supergiant stars, it was possible for the first time to attempt a precise classification of the circumstellar dust mineralogy.

The presence of a broad 9.8 μm feature, either in emission or absorption, and a secondary one between 16 and 20 μm, was readily associated with vibrations of the Si-O bond in silicate dust. A mixture of olivines ($[Mg_xFe_{2-x}]SiO_4$) and pyroxenes ($[Mg_xFe_{1-x}]SiO_3$) with amorphous structures is now accepted as the main component of dust in O-rich circumstellar envelopes. Recent SWS spectra obtained with the infrared satellite ISO (see e.g. Waters et al., 1996), however, suggest the presence of minor quantities of crystalline grains in the envelopes of some very evolved AGB and post-AGB objects. Secondary features already observed in the IRAS database, as the famous 13 μm emission feature, were instead attributed to corundum (Al_2O_3, see e.g. Onaka et al. 1989), or other oxides (as SiO_2, see Speck 1998).

The LRS of C-rich envelopes, on the other end, exhibit a rather flat spectrum, where the main feature is a narrow emission line at 11.2 μm, associated to SiC. The main component of carbonaceous dust, however, is amorphous carbon, consisting of graphite crystals arranged in an amorphous conglomerate ("sooth", making these stars similar to "smoking chimneys"). Another important component of C-rich envelopes are the PAH, which are known to play a central role in carbonaceous dust formation processes (Cherchneff et al., 1992). Their observation, however, is limited to post-AGB end Planetary Nebulæ (PN) halos, where they are excited by the energetic UV photons emitted by the hot central star.

The dichotomy between O-rich and C-rich dust in circumstellar envelopes is largely regulated by the chemistry of the CO molecule (Dominik et al., 1993). A strongly bonded compound, CO does not interact with the other circumstellar particles. Since it is one of the very first molecules to form, CO rapidly depletes the circumstellar gas from the less abundant element between O and C. Stars with $C/O \lesssim 1$ (O-rich stars) will thus be forced to form oxidic dust, while carbon stars ($C/O \gtrsim 1$) will be left with an overabundance of C atoms, leading to the formation of dust in a C-rich chemistry. There are exceptions, to this rather strict rule: the 9.8 μm silicate feature was in fact observed in a few IRAS carbon star spectra (Little-Marenin, 1986; Willems & de Jong, 1986). The meaning of these observations is still quite uncertain, even though binarity, or changes in the parent star, have been proposed to solve the mystery.

The efforts to better understand the mineralogy of circumstellar dust and the details of its formation have dominated the research of the last decade, with two basic approaches: theoretical and laboratory determination of dust opacities (see Speck 1998 for a recent review), and modeling of dust condensation in circumstellar environments (Winters et al., 1994; Windsteig et al., 1997; Höfner & Dorfi, 1997). Despite the advances in the last years, there are still various degrees of uncertainties, mainly due to radiative transfer effects limiting our ability to derive dust opacities from observational data, and because the dust composition of individual sources can be very different (see discussion in section 4).

To conclude this section, it is worth noting that a completely independent confirmation of the stellar origin of interstellar dust is obtained by the analysis of meteorites, which in some cases contain small inclusions of refractory grains characterized by anomalous isotopical composition. The measured isotopical abundances, that cannot be explained if the grain where formed inside the presolar nebula, demonstrate their provenience from the circumstellar envelopes of AGB stars (Gallino et al., 1990). This exciting discovery realizes an ancient dream of astronomers, allowing the direct analysis of "stardust" and stellar materials in the comfort of their own laboratory.

1.2.4 Extragalactic dust

In June 1957 Fritz Zwicky presented at the Flagstaff meeting of the Astronomical Society of the Pacific the results of a large scale investigation on the "Non-Uniformities in the Apparent Distribution of Cluster of Galaxies". The statistical analysis, carried out on fields photographed with the Mount Palomar 18-inch and 48-inch Schmidt telescopes, as well as the 200-inch Hale reflector, contained the first real indication of a non uniform distribution of clusters of galaxies. By finding an average lower density of faint galaxies in proximity of intrinsically brighter ones, he suggested that "*... [intergalactic] dust exists in all intergalactic space, but is preferentially located in the rich clusters of galaxies*"[5]. Unfortunately, he went so far to predict the existence of extragalactic dust everywhere in the universe, to the point of negating his own evidences of superclustering, by explaining the cluster anisotropy as an extinction effect only.

His observations of the anticorrelation between faint galaxies and rich clusters, however, was confirmed many years later by Bogart & Wagoner (1973) while looking for clustering effects between quasars (QSO) and clus-

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[5] Zwicky (1957)

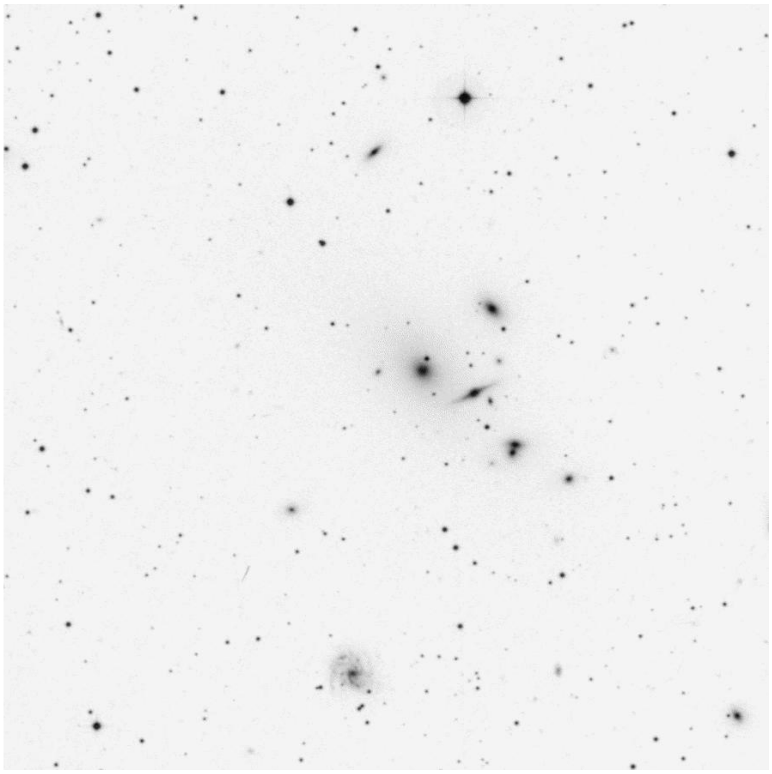

Fig. 1.3.— Digitized Sky Survey image of Abell cluster 262.

ters of galaxies. They found this discovery "*somewhat contradictory*" and rejected as unlikely the hypothesis of dust extinction as the explanation. In their conclusions, however, they mentioned that Karachentsev & Lipovetskii (1969) and de Vancouleurs et al. (1972) did measure an average obscuration of about 0.2 magnitudes of the background galaxies.

More recently, Boyle et al. (1988) made a new search looking for correlations between the position of high-redshift quasars and low redshift galaxies. They did not find it, but were perplexed to obtain a significant (4σ) deficiency of QSOs (up to 30%) in a radius of 4 arcmin from galaxies lying in a cluster. They attributed the effect as a result of dust extinction, measuring again $A_B \simeq 0.2$. A later survey (Romani & Maoz, 1992) concluded that an average value of $A_B \sim 0.5$ mag (or a very patchy distribution) was necessary to explain the observed anticorrelation between quasars and their sample of Abell clusters. However, when Ferguson (1993), and later Maoz (1995) searched for the reddening that should accompany such strong extinction, they didn't find any positive results, raising new doubts about the presence of substantial amounts of dust in clusters of galaxies. Hu (1992), on the other end, in a series of papers looking at the UV-to-optical line ratio from the emission of background galaxies in *cooling flow* clusters, measured an E_{B-V} reddening of about the expected value (~ 0.19).

In an attempt to reconcile the contradicting observations, the amount of reddening that should be expected for the measured extinction was computed by Aguirre (1999), with the assumption of a grain population biased towards small sizes. He concluded that such dust would be too gray to produce an observable reddening, but opaque enough to count for the observed type I supernova dimming, thus reconciling cosmological models with observational data *without* requiring an accelerating universe! As in the case of Zwicky, this is another example of the really profound consequences that the inclusion of dust may have in our view of the structure of the universe.

It should be clear, by now, that the presence of dust in the ICM is highly controversial, not only because of the difficult task of providing observational evidences, but also for the important consequences that dust in cluster of galaxies would have for many fundamental cosmological questions.

The main reason why it is so difficult to accept the presence of dust in the extragalactic space is that the ICM environment is very hostile to the survival of dust. With temperatures ranging between 10^6 and 10^9 K, and densities of the order of $10^{-6} - 10^{-2}$ cm^{-3}, the gas in the ICM is very efficient to destroy dust grain on timescales of $10^6 - 10^8$ yr (see discussion in section 2.3.3). If dust exist in such conditions, it either implies a recent episode of dust injection from the galaxies in the cluster, or a mechanism for dust formation *in situ*. As anticipated in section 1.2.1, there are evidences that support both possibilities.

The fact that ICM is chemically enriched, suggests some sort of interaction with the ISM of the galaxies in the clusters, since any trace of metals in the ICM should be traced back to stellar nucleosynthesis. Strong stellar winds in starburst galaxies can throw into the gravitational well of the cluster a fraction of their newly enriched ISM (gas *and dust*), as explained in Matteucci & Gibson (1995). Ram pressure stripping at the passage of a galaxy in the central regions of a cluster can also contribute in maintaining a certain amount of ICM dust.

Radiative cooling in the denser regions of some clusters, acting as *cooling flows*, can also give rise to the conditions for dust formation. As predicted by Fabian et al. (1994), when cold matter slowly accumulates at the core of the cluster, it may form cold clouds, and maybe even stars, explaining the alignment of some cooling flows with their optical emission.

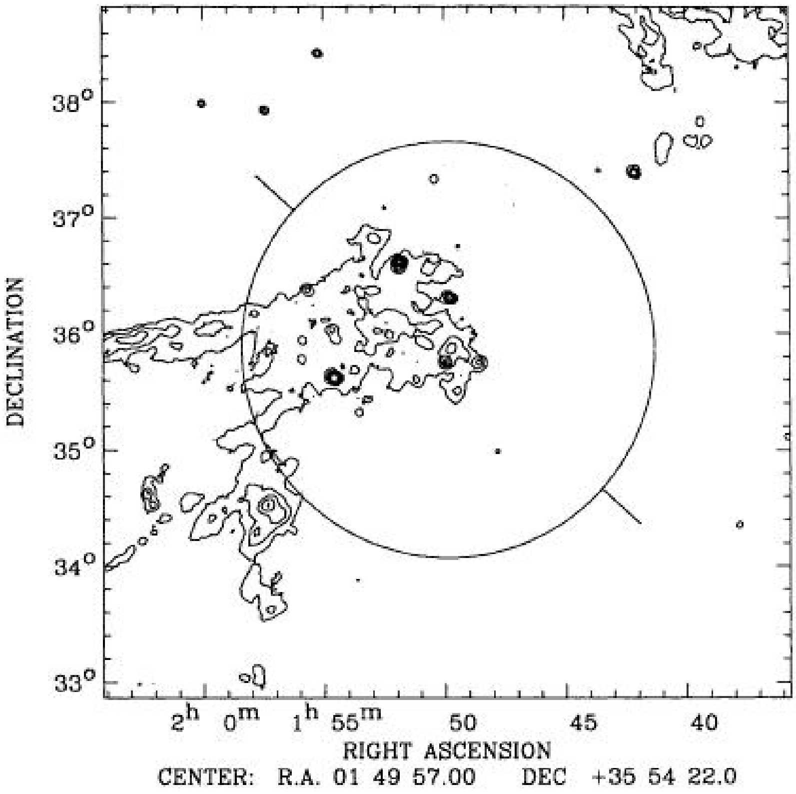

FIG. 1.4.— IRAS image of Abell cluster 262 at 100 μm. The circle marks the cluster radius, and the vectors indicate the cluster's major axis. Contours show intensity levels ranging from 2 to 10 σ above the mean background noise, in steps of 1 σ. Adapted from Wise et al. (1993).

A more direct way to solve the controversy, looking for direct evidences of ICM dust, would be to search for the thermal emission of grains heated by the hot ICM plasma. Since the expected "mean" temperature of the grains, is ~ 30 K, the spectral region of choice for a detection should be the far-infrared/millimetric domain.

Several groups have attempted to scan the IRAS database in search of diffused far-IR emissions (60 – 100 μm) from cluster of galaxies (Bregman et al., 1990; Wise et al., 1993; Cox et al., 1995; Bregman & Cox, 1997). These surveys obtained mixed results, finding a "positive" detection of "warm" (24 – 33 K) dust emission for about 10% of the observed clusters, but with a rather low statistical significance (between 3 and 5 σ). Similar searches in the sub-millimeter by Annis & Jewitt (1993) and at the wavelength of the CO (J=1→0) line by Grabelsky & Ulmer (1990) did not give positive results.

An example of positive detection in Wise et al. (1993) is given in figure 1.4; the low spatial resolution of the IRAS scan does not allow to determine the exact position of the diffuse emission, thus making impossible to distinguish if the dust is diffused in the hot ICM, or included in the dominant member of the cluster. A more careful analysis and calibration of ISO data may be able to solve the puzzle, but there are no conclusive answers thus far (Cox & Bregman, 1997). In the meantime, and waiting for the upcoming SIRTF observatory, the available observations suggest that ICM dust may be a short lived phase that occurs in particular conditions, for only a fraction of the clusters of galaxies.