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IRAS studies of the nature of interstellar dust and planetary nebulae

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Document Version

Publisher's PDF, also known as Version of record

Publication date:

1987

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Leene, A. (1987). *IRAS studies of the nature of interstellar dust and planetary nebulae*. s.n.

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Chapter I

General summary

The IRAS data has provided a huge quantity of data, which will be used far into the future. It has its impact on many astronomical research fields from asteroids to cosmology. I have contributed to two different subjects touched upon by the IRAS data. The first subject involves the infrared emission of small grains and the nature of these small grains. The second subject involves the far-infrared emission as observed from resolved planetary nebulae. Both subjects will be introduced here and my contribution to astronomy will be put in the context of work done by many others.

1. Small grains

One of the most interesting discoveries of the IRAS mission is the large scale emission in the mid-infrared (12-25 μm). This extended emission is visible under a variety of interstellar conditions. Beichman et al. (1984) reported the first evidence for extended 12 μm emission in Lynds 255 at the 164th AAS meeting in Baltimore. Further evidence was presented at the colloquium on Nearby Molecular Clouds held in Toulouse, France in 1984 (Boulanger et al., 1985; Leene & Beichman, 1985). After the publication of the IRAS Skyflux images (IRAS Explanatory Supplement, 1985) it became clear that this mid-infrared emission is widespread. It can readily be observed by inspecting one of the Skyflux photographs.

The IRAS data are however not the first evidence for extended mid-infrared emission. Data of Price (1981) obtained with a rocket borne telescope show evidence for extended emission at 4, 11 and 20 μm . This data was limited to within 5° of the galactic plane. The flux density ratio between the 11 and 20 μm bands of Price indicates a black body colour temperature of 500 K. One explanation for the diffuse emission could be the existence of an unresolved background of point sources. These sources could be circumstellar dust shells and/or compact HII regions. The analysis of Price showed that both types of sources are not abundant enough to explain the observations.

The main problem with the mid-infrared emission is its large colour temperature and its large brightness. The observed brightnesses are much larger than is expected with the "standard" dust models. The reflection nebula associated with the R CrA molecular cloud (Leene, 1986; Chapter 3) indicates that the brightness of the $12\ \mu\text{m}$ emission is a factor $10^6 - 10^{12}$ larger than would be expected with the Mathis et al. (1977) model (Draine & Anderson, 1985). In the R CrA cloud there is no evidence for extra or abnormal heating sources. The heating seems to be carried out by the Interstellar Radiation Field (ISRF). The ISRF is apparently able to provide enough energy to explain the observations.

A more intriguing problem is raised by the observed colour temperature. The observations of Lynds 255 indicate a colour temperature of 200 K. The HI cloud analysed by Boulanger et al. (1985b) indicates a colour temperature of 320 K. The reflection nebula in RCrA is even more extreme with a temperature of 390 K (Leene, 1986). The existence of such extreme temperatures was later confirmed by observations of the "Blob" (Laureijs et al., 1986). As the dust heating is caused by the ISRF, it is clear that there exists a problem. The ISRF is able to heat the dust grains to roughly 11 K for silicate grains and 19 K for graphite grains (Mezger et al., 1982). This is much cooler than the large temperatures inferred from the $12/25\ \mu\text{m}$ brightness ratio. But also the $60/100\ \mu\text{m}$ brightness ratios indicate a larger temperature. In the RCrA cloud this temperature is 23 K and in the HI cloud of Boulanger et al. (1985) this is 26 K.

Again the IRAS data are not the first evidence for anomalous large temperatures. Sellgren et al. (1983) reported observations of extended near-infrared emission from visual reflection nebulae. They obtained near-infrared spectra (1.9 to $3.7\ \mu\text{m}$) of the extended emission of the reflection nebulae NGC 7023 and NGC 2023. The spectra indicate an underlying continuum with a colour temperature of 1000 K. Subsequent observations of the extended emission (Sellgren, 1984) showed the absence of a radial colour gradient in these reflection nebulae. This is impossible to explain with an equilibrium heating process of the dust grains.

The absence of a colour gradient can be explained by a thermal fluctuation model of small grains (Sellgren, 1984). In this model small grains are heated to high temperatures after the absorption of a single photon. Due to the very small heat capacity of the small grain it can reach very large temperatures. The observed colour temperature of 1000 K requires a grain radius of 1 nm. Previously thermal fluctuations have been proposed, but have been restricted to the larger grain sizes and the temperatures reached were not very high (Duley, 1973; Greenberg & Hong, 1974; Purcell, 1976).

Purcell (1976) allowed for grain sizes down to 5 nm and was able to reach temperatures of 50.5 K. A reanalysis of the problem by Draine &

Anderson (1985) with grain sizes down to 0.5 nm radius gave temperatures up to 300 to 600 K. The predictions made by Draine & Anderson (1985) of the expected IRAS brightness ratio's have been compared to the data of Leene (1986) and Boulanger et al. (1985). It shows that the model is still unable to explain the observations. Even with an increased amount of very small grains (< 10 nm) the predicted 12/100 μm brightness ratio is still a factor six too low.

This discrepancy most likely lies in the properties of the small grains. Very small grains (< 1 nm) were first initially proposed by Platt (1956). These grains are however so small that they no longer can be regarded as grains, one should speak of large molecules. The grains proposed by Sellgren (1984) contain some 80 atoms. For such large molecules the optical properties of grains, as have been used by Draine & Anderson (1985), are no longer applicable.

An important indicator to the nature of the near-infrared emission was the absence of a colour gradient. In the observations of the R CrA cloud no evidence of large scale gradients was observed, but the source morphology hampered the analysis somewhat. Castelaz et al. (1987) clearly show that the 12 and 25 μm emission around stars in the Pleiades does not show any temperature gradient. The cool dust observed at 60 and 100 μm however does show a temperature gradient.

By combining the data of various objects Ryter et al. (1987) show that the small grains are destroyed with increasing radiation densities. At low radiation densities these small grains will also contribute to the flux of the 60 μm band. Observations of the Rosette nebula confirm the lack of small grains inside HII regions (Cox & Leene, 1987, in prep.). It is also shown that the grain size distribution is bimodal. The simple extrapolation of the Mathis et al. (1977) size distribution, as has been used by Puget et al. (1985), is not realistic.

Evidence for such large molecules has been growing rapidly during the last years. In 1973 Gillet et al. reported the observation of two narrow resolved spectral features in the 8-13 μm spectrum of NGC 7027. In total some 5 features (at 3.3, 6.2, 7.7, 8.6 and 11.3 μm) have been identified. For a long time no good explanation could be provided. The features always occur in common and apparently in UV-photon rich environments. The features are most likely caused by grains or grain mantles, as the features do not break up under high spectral resolution (Willner, 1983).

In 1984 Léger & Puget proposed that large polycyclic aromatic molecules are responsible for these infrared features. A comparison of the spectrum of Coronene ($C_{24}H_{12}$) with the observed spectra gives an excellent match. The generic name for these molecules are polycyclic aromatic hydrocarbons (PAH's). For their structure see Fig. 3 of the dutch summary.

PAH's are very abundant on earth and they occur in large quantities in coal products, car exhaust soot, oil products, cigarette fumes, etc.

The excitation of the infrared features for a long time proved to be the bottleneck in their explanation. However with the transient heating by small grains, as has been proposed by Sellgren, this problem has been solved. Léger & Puget (1984) show that these PAH's are not destroyed by sublimation, when they absorb an energetic photon. The transient heating process provides an UV/IR conversion efficiency which is large enough to be able to explain the infrared features. The correlation between hot grains and the infrared features seems to be confirmed by the detection of the infrared features in NGC 7023 and NGC 2023 (Sellgren et al, 1985).

The hot dust component seen by IRAS seems to be the same as the hot grains observed by Sellgren. Furthermore three of the infrared features (at 7.7, 8.6 and 11.3 μm) are also contained in the IRAS 12 μm band. Puget et al. (1985) calculate the spectrum for a size distribution of grains, including Coronene, under interstellar conditions. They predict that these molecules should indeed be an important contributor to the IRAS 12 μm band. Furthermore they show that an important fraction of the carbon abundance should be contained in PAH's. For the data of RCrA cloud this would even imply that 17% of the carbon abundance is locked up in PAH's. Model calculations show that the very small grains must be graphitic in nature and silicates, which were the main contributor in the Draine & Anderson (1985) model, are ruled out (Désert et al, 1986).

The energy emitted at 12 μm is 25-100% of the energy emitted at 100 μm . Where is this energy absorbed? Work done on the extinction curve shows that it consists of three rather independent components: the visual, the 220 nm bump and the far ultraviolet (Chlewicki, 1985). Spectra of large PAH's published by Donn (1968) indicate that they all have an absorption peak around 220 nm. Thus these PAH's might be at the origin of the 220 nm bump. The 220 nm absorption bump is very constant in wavelength and width (Fitzpatrick et al., 1986) indicating that a single grain species is responsible. Many explanations have been proposed, but none has been satisfactory (Savage & Mathis, 1979).

Whether PAH's are at the origin of the 220 nm bump has been analysed by Cox & Leene (1987; Chapter 4). They have analysed a correlation between the strength of the UV bump, as determined from ANS data, and the 12/100 μm brightness ratio's towards several diffuse line of sights. For a wide range of UV bumps the 12/100 μm ratio remains very constant. No correlation seems to be present. This is confirmed by observations of single objects. In some objects the UV bump is virtually absent and the infrared features are very prominent. Thus the PAH's are not responsible for the 220 nm bump.

It is much more likely that the PAH's are responsible for the extinction rise towards the far ultraviolet. Andriessse & de Vries (1974) introduced the Platt particles in order to explain the extinction in the far ultraviolet. The nature of the 220 nm bump remains unclear. Hecht (1986) proposed that the bump is caused by small hydrogen-free carbon grains and predicts a correlation between the dust temperature and the width of the bump. An analysis of Leene & Cox (1987; Chapter 5) shows that only the bump height is dependent on the 60/100 μm brightness ratio. This indicates that the number of "bump" grains decreases as the strength of the ISRF increases. Most likely the "bump" grains are destroyed.

The existence of PAH's could have its effect on several other, as yet unsolved, problems in astronomy. In the optical there exist a series of 50 interstellar absorption bands (the Diffuse Interstellar Bands). Since their discovery (Merrill, 1934) they could not be identified (van der Zwet, 1986). However the PAH's might provide a viable explanation (Léger & d'Hendecourt, 1985; van der Zwet & Allamandola, 1985; Crawford et al., 1985).

In the Red Rectangle there is an unexplained excess of red light, which is also seen in other objects. Chlewicki & Laureys (1986) propose that this excess is caused by fluorescence from PAH molecules. PAH's might also be the main contribuant to the heating of galactic HI. D'Hendecourt & Léger (1987) propose that heating by the photoelectric effect on PAH's can provide 80-90% of the energy input to heat the HI. The PAH's have also an important effect on the carbon reaction schemes (Omont, 1986) and many of them need to be adapted.

The existence of PAH's seems to have opened a Pandora's Box. Many problems could be solved, but much work remains to be done. One of the main questions is what the PAH's look like in space and what they are. For this laboratory work is needed in order to synthesize possible species. Comparison of laboratory spectra with astronomical data remains one of the biggest problems. Many observations need space or rocket-borne instruments. These will only come available in the early nineties with telescopes such as ISO.

2. Extended Planetary Nebulae

The dust described in the previous section is most likely produced in the last stages of stellar evolution, i.e. in the winds of red giants on the Asymptotic Giant Branch (AGB) and/or in Planetary Nebulae. In fact one of the typical examples for the unidentified infrared features is the planetary nebula NGC 7027 (Russell et al., 1979). Planetary nebulae are presumed to

be formed by the onset of a stellar wind, which is able to remove the outer layers of the stellar atmosphere (Schmidt-Voigt & Köppen, 1987). This progenitor is most likely a red giant on the AGB (c.f. Kwok, 1982). However both the formation of dust and the nature of the progenitor are still very unclear. Therefore the analysis of the far infrared emission might provide some insight.

The first detection of dust in planetary nebulae has been made by Gillet et al. (1967). This detection came as a big surprise. Previously it had been assumed that dust could not survive the strong radiation field of the central star. Later it became clear that dust was a common phenomenon in planetary nebulae (c.f. Cohen & Barlow, 1974, 1980), although the measurements were limited to the spectral windows accessible from earth. The study of dust in planetary nebulae mainly was a study of NGC 7027 (ironically this nebula was not observed by IRAS).

The observations of 13 planetary nebulae in the far infrared by Moseley (1980) provided more insight. The nebulae predominantly radiate at the far infrared wavelengths. Natta & Panagia (1981) used this data to analyse the evolution of dust grains in planetary nebulae. They found that the average size of the grains decreases with the nebular size and thus with time. But the number of grains increase with time. Thus either the grains are fragmented or the properties of the originally ejected grains vary systematically with radius. The dust to gas masses seemed rather low ($< 3 \cdot 10^{-4}$), implying that planetary nebulae dilute the dust in the Interstellar Medium, rather than enrich it.

The IRAS database greatly enlarged our far infrared view on planetary nebulae. Virtually all known planetary nebulae can be found in the IRAS data. The first analysis of 46 bright planetary nebulae observed by IRAS has been carried out by Pottasch et al. (1984). All nebulae predominantly radiate at 25 and 60 μm . The dust temperature as determined from the longer wavelengths shows a trend with nebular radius: the larger the nebula, the colder the dust. This is most easily explained by an expansion of the nebula. The dust is heated by trapped Ly α photons and other resonance lines, like the CIV line. Infrared bright planetary nebulae require an additional heating source, which is most likely direct starlight. The dust to gas ratio was shown to decrease with nebular radius, confirming the results of Natta & Panagia (1981). A further analysis of weaker planetary nebulae by Iyengar (1986) confirmed the results of Pottasch et al. (1984).

The analysis of IRAS Low Resolution Spectrometer data (Pottasch et al., 1984, 1985, 1986) shows that line emission is very pronounced at the near-infrared wavelengths. The most important lines are: NeVI (7.65 μm), ArIII (9.0 μm), SIV (10.52 μm), NeII (12.81 μm), NeV (14.3 μm) and SIII (18.7 μm) in the LRS wavelength regime (8-22 μm). These lines can greatly

influence the Planetary Nebula flux densities as listed in the IRAS Point Source Catalog: 70-80% of the flux can be due to line emission. This effect is clearly present in the IRAS images of NGC 7293 (Leene & Pottasch, 1987; Chapter 6).

The morphology of NGC 7293 at the four wavelengths is totally different. This can only be explained in terms of line emission. At 12 μm the data shows a ring, which is caused by the SIV line. At 25 μm the data is centrally concentrated, due to the OIV line. At 60 and 100 μm the emission is due to dust and lies within the 12 μm perimeter. The effect of line emission on the 60 and 100 μm data is not very clear yet. Comparison of five nebulae observed by Dinerstein et al. (1985) in the OIII lines with the IRAS data, show that only 10% of the IRAS Point Source flux densities are due to lines, but the existence of other lines and the beam size differences might change this number.

Natta & Panagia (1981) assumed that the bulk of the far infrared emission arises from large, cool grains, whereas the 10 μm emission comes from small, hot dust grains in the same region. The model of Kwok (1980) for NGC 7027 however assumes that these two components are not well mixed. The hot dust lies within the HII region and is due to the planetary nebula ejection phenomenon. The cool dust is a remnant of the AGB wind and lies outside the hot dust. Unfortunately very little information was available on the distribution of the infrared emission.

The distribution of the infrared emission is a key parameter in order to distinguish between the Kwok (1980) and the Natta & Panagia (1981) model. Observations of Aitken & Roche (1983) and Bentley et al. (1984) show no clear evidence of a difference in brightness distribution at various near-infrared wavelengths of NGC 7027 and NGC 6543. Except for the 11.3 μm feature all wavelengths have the same distribution. At the longer wavelengths no information is available at all. The data of Leene & Pottasch (1987) on NGC 7293 show that the dust lies well within the ionized region. Further the 60 and 100 μm brightness profiles are very similar, indicating the existence of a constant temperature. Observations of NGC 6853 (Zhang et al., 1987; Chapter 7) confirms these results.

In order to analyse the distribution of dust in more nebulae the IRAS Pointed Observations towards planetary nebulae have been analysed (Leene et al., 1987; Chapter 8). Of the 67 nebulae observed only 10 proved to be resolved. These 10 nebulae supported the results on NGC 7293 and NGC 6853. There is no evidence for a temperature gradient. However there exists some circumstantial evidence for a temperature gradient in BD +30 3639 and NGC 6543. The near infrared emission of these nebulae seems to originate in a smaller region than the far infrared emission. It is however unclear whether this is caused by a difference in beam sizes and/or

by the ground based chopping techniques, which remove extended infrared emission or is in fact real.

The far infrared emission seems to be limited to the $H\alpha$ emitting zones of planetary nebulae. A similar observation has been made at near-infrared wavelengths for A30 and A78 (Cohen et al., 1977), where the main emission originates in bright OIII emitting knots. The lack of dust emission outside the HII region seems somewhat surprising. It indicates that the nebulae are density bounded and that there doesn't exist any remnant of an AGB wind. Optical halo's have been found for many nebulae and have been attributed to multiple shell ejections (Jewitt et al., 1986). The non-detection of an infrared halo is somewhat hampered by the data: the small images of the pointed observations will remove large halo's; the existence of infrared cirrus corrupts the definition of a background; the sensitivity of the data hampers the detection of very cool dust.

The IRAS data has increased our knowledge of dust in planetary nebulae, but has also posed some new questions. The apparent non-existence of an infrared halo could be an important parameter to the nature of the progenitor of the nebulae. However it needs further attention. The effect of line emission on the $25 \mu\text{m}$ (and also the longer wavelengths) is totally unknown. Future space missions should resolve this question.

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