Evidence for the Heating of Atomic Interstellar Gas by PAHs

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ABSTRACT

We report a strong correlation between the [CII] 158 µm cooling line and the mid-infrared flux in the 5-10 µm range in a wide variety of star-forming galaxies. The mid-infrared flux is dominated by Aromatic Feature Emission (AFE), which is thought to arise from large polycyclic aromatic hydrocarbon molecules or “PAHs” and is generally associated with the smallest interstellar grains. The [CII] line is the dominant gas coolant in most regions of atomic interstellar gas, and therefore reflects the heating input to the gas. The ratio of these two quantities, [CII]/AFE, remains nearly constant around 1.5% against variations in the ratio of the IRAS 60 µm band flux to the 100 µm band flux, R(60/100). This is in contrast to the drop in the [CII]/FIR ratio with increasing R(60/100), which signals higher dust temperatures and more intense radiation fields. We interpret the stable [CII]/AFE ratio as evidence that gas heating is dominated by the PAHs or small grains, which are also AFE carriers, over a wide range of conditions. The trend of decreasing [CII]/FIR and AFE/FIR with increasing radiation field suggests a decrease in the importance of PAHs or small grains relative to large grains both in gas heating and in dust cooling. We summarize the observed trends and suggest two plausible scenarios.

Subject headings: galaxies:ISM—dust—ISM:lines and bands:atoms

1. Introduction

The heating and cooling processes in the interstellar medium are crucial to determining its physical state in equilibrium. Photoelectrons from dust grains or Polycyclic Aromatic

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Hydrocarbons (PAHs) are thought to dominate the heating of neutral gas (Watson 1972; Hollenbach & Tielens 1999). In an indirect and inefficient mechanism, incident far-ultraviolet photons with energies high enough to eject electrons from dust grains \((h\nu \gtrsim 6 \text{ eV})\) heat the gas via these photoelectrons, with a typical efficiency of \(0.1 - 1\%\). This efficiency is determined by microphysics of the grains, in particular the work function and the resultant photoelectric yield, and therefore the charge of the grains. It is defined as the ratio of the gas heating rate by photoelectrons to grain heating rate by far-ultraviolet photons. The grain heating is radiated away in the infrared. The gas heating is also radiated away in the infrared, primarily via fine-structure lines such as \([\text{CII}]\) (158 \(\mu\text{m}\)) and \([\text{OI}]\) (63 \(\mu\text{m}\)), with \([\text{CII}]\) dominant at lower densities and temperatures. The photoelectric effect on dust thus provides the main coupling of the far-ultraviolet radiation field to interstellar gas outside of H II regions, and is a major process in photodissociation regions (Hollenbach & Tielens 1999). The heating efficiency of the photoelectric effect is traditionally measured by the flux ratio \(((\text{CII})+\text{[OI]})/\text{FIR}\), where FIR is the dust continuum in the far-infrared.

The physical description of the photoelectric effect and its dependence on various parameters is fairly well developed. In particular, it has been established for some time that smaller grains are more effective at generating photoelectrons, because of their lower potential barrier to escaping electrons, and because the emerging electron is less likely to lose energy as it works its way from the ejection site within the grain to the outside. Given the typical grain size distributions, the net result is that the smallest grains dominate the photoelectric heating (Watson 1972, Jura 1976, de Jong 1977, Draine 1978, Bakes & Tielens 1994). d’Hendecourt & Léger (1987) argued that PAHs may be the key to H I interstellar gas heating in clouds and intercloud regions, assuming they carry a plausible 10\% of interstellar carbon. On the other hand, in a standard Bakes & Tielens model of the Orion Bar about half of the total photoelectric heating is due to small grains with radii less than 15 Å, typical of PAHs and smaller molecules. The importance of PAHs to the ionization balance and chemistry of the interstellar medium is discussed by Lepp & Dalgarno (1988).

Quite independently, the hypothesis of very small grains heated stochastically to emit at wavelengths shorter than expected for their radiative environment was proposed by Andriessse (1978), and by Sellgren (1984) to explain her data on reflection nebulae which showed an excess in the near infrared with abnormally elevated apparent temperatures. IRAS revealed ubiquitous dust emission at 12 \(\mu\text{m}\), and very small grains were accepted as widespread (Beichman 1987). Combined with rudimentary spectral data, the IRAS 12 \(\mu\text{m}\) emission was associated with Aromatic Features (Puget & Leger 1989). Detailed spectra with ISO left no doubt that the mid-infrared emission from dust in all but the most extreme environments is dominated by the Aromatic Features, and is therefore a good tracer of PAHs (Tielens et al. 1999). Helou et al. (2000) recently established that the mid-infrared
spectra of normal galaxies are almost constant in shape, and dominated by the Aromatic Features in Emission (AFE), which carry from a few percent up to 20% of the total infrared luminosity.

2. The [CII] “Deficiency”

Malhotra et al. (1997 and 2000a) reported ISO observations of 60 normal galaxies spanning a broad range in R(60/100), FIR/B-band flux and morphology, and demonstrated that [CII]/FIR decreases as R(60/100) increases in galaxies. Since most galaxies have ratios \[\text{[CII]}/\text{FIR} \sim 10^{-3} - 10^{-2}\], those with ratios \(< 10^{-3}\) were said to be “deficient.” Since R(60/100) measures average temperatures of the large dust grain population, it increases with increasing far-ultraviolet flux \(G_0\). The lowest [CII]/FIR ratios are observed in warmer and more actively star-forming galaxies. There have been many explanations proposed, such as optical depth effects, heating radiation too soft to ionize carbon, or the influence of an active galactic nucleus (Malhotra et al. 1997 and 2000a, Luhman et al. 1998, Genzel & Césarsky 2000). The currently prevailing opinion, however, points to decreased efficiency of photoelectric heating due to positively charged grains. In the more actively star-forming and warmer galaxies, the far-ultraviolet flux is higher. A higher ratio of far-ultraviolet flux to gas density, \(G_0/n\), leads to more positively charged grains and therefore to lower photoelectric efficiency.

It is possible that the decrease in [CII]/FIR, instead of indicating a decrease in the heating efficiency, might result from the gas cooling via the other principal channel, [OI] 63 \(\mu\)m. However, the combined flux in the cooling lines normalized to the far-infrared emission ([CII]+[OI])/FIR still shows a clear trend towards smaller values for the more actively star-forming galaxies. [OI] 63 \(\mu\)m does become the dominant coolant for galaxies showing warmer dust temperatures, but this relative rise does not compensate for the decrease in [CII] relative to FIR.

3. A New Normalization?

The “deficiency” seen in [CII] is defined by comparison to the far-infrared emission from dust grains. Far-infrared emission measures the radiation emitted by large or “classical” grains that are in thermal equilibrium, maintaining a nearly constant temperature. If photoelectric heating is dominated by small grains, a more appropriate normalization factor for [CII] line should be the emission from these grains (Helou 1999). The smallest grains
briefly reach very high effective temperatures with the absorption of a single photon and therefore emit in the mid-infrared. In the PAH picture, this can be viewed as a fluorescence phenomenon from a molecule at high excitation temperature. In any case, because of the invariant AFE spectrum, the mid-infrared flux tracks well the total heating of this grain population. Figure 1 (top panel) shows the [CII] line strength normalized to the AFE flux plotted against R(60/100). The AFE flux is derived from ISO-CAM observations with broadband filter at 6.75 μm (Dale et al. 2000), which is very well matched to measuring the AFE. The observed flux is scaled up by a factor of 1.17 to recover the integrated 5–10 μm flux. The scaling factor derives from the properties of the ISO-CAM 6.75 μm filter and the average mid-infrared spectrum of Helou et al. (2000). We see not only a lack of any trend of decreasing [CII]/AFE with R(60/100), but the scatter in the [CII]/AFE values is about half the dispersion in [CII]/FIR (comparing top and bottom panels of Figure 1). This suggests that there is indeed a special connection between mid-infrared emission and [CII] emission.

3.1. Scatter and Outliers

The measured line fluxes have 30% uncertainty which contributes substantially to the observed scatter of $\sigma = 0.18$ dex ($\approx 50\%$). The 5–10 μm flux attributed to AFE also includes some contribution from stellar light which is not significant except in early type galaxies (Malhotra et al. 2000b). The mid-infrared emission is from grains heated by far-ultraviolet as well as optical photons (Uchida, Sellgren & Werner 1998), whereas only far-ultraviolet photons at energies typically greater than 6 eV are effective in heating the gas. Thus the variation of the hardness of the radiation field also introduces some scatter in the observed [CII]/AFE value. Some fraction of [CII] flux also arises in ionized regions where the photoelectric effect is not the dominant heating mechanism (Petuchowski & Bennett 1993, Heiles 1994, Malhotra et al. 2000a); extreme cases of this offset are discussed further below. With all these terms, it is remarkable that the dispersion in [CII]/AFE is not greater than measured.

The lowest value of [CII]/AFE in Figure 1 represents NGC 4418 and is more than 5σ away from the mean. As discussed by Lu et al. (2000), the mid-infrared spectrum of NGC 4418 is not typical of star-forming galaxies. It shows none of the familiar aromatic features but instead has a very broad plateau between 6 and 8.5 μm. This may be a partial view of the continuum along with the 9.7 μm silicate absorption feature. In any case the imaging with the ISO-CAM filter at 6.75 μm does not measure aromatic feature emission for NGC 4418. The upper limit in [CII]/AFE in Figure 1 represents IC 860, from which [CII] was not detected. The mid-infrared spectrum of IC 860 appears similar to that of
NGC 4418, but has a very low signal-to-noise ratio (Lu et al. 2000). Both galaxies are OH mega-masers.

Two of the three highest values of [CII]/AFE in Figure 1 belong to galaxies that have [NII]/FIR a factor of ten and 4$\sigma$ greater than the mean value. As discussed by Malhotra et al. (2000a), this indicates a larger than average contribution from H II regions to the [CII] line emission from these galaxies, which appears to cause somewhat elevated [CII]/AFE.

3.2. [OI] λ 63 µm

Since [OI](63 µm) is also an important coolant, a more appropriate quantity to plot might be the total gas cooling with respect to the AFE flux, i.e. ([CII]+[OI])/AFE. In Figure 2 this quantity is plotted against R(60/100), showing a larger scatter in the ([CII]+[OI])/AFE, but essentially the same behavior as the ratio [CII]/AFE up to R(60/100)~ 0.65. For greater values, the scatter increases quickly as does the mean ratio. This is consistent with [CII] being the dominant cooling line for all but the warmest galaxies (Malhotra et al. 2000a). The energy level and critical density for [OI] (63 µm) is higher than for [CII], so this line is expected to become more important relative to [CII] in warmer and dense gas, which is associated with greater values of $G_0/n$ and R(60/100) in photodissociation region models.

4. Discussion

The empirical results above strongly suggest that the smallest particles which produce the mid-infrared emission are a key contributor to the photoelectric effect in photodissociation regions. Theoretical studies of the Orion photodissociation region where the values of $G_0$ and $n$ are elevated and the ratio $G_0/n$ is also moderately high, show that about half the photoelectric heating is due to particles smaller than 15 Å (Bakes & Tielens 1994). The observed constancy of the [CII]/AFE ratio, in a sample where the [CII]/FIR ratio shows larger systematic variations, indicates that the role of small grains in heating the gas may be even more prominent. The interpretation of this empirical picture however is hindered by serious uncertainties in the properties of the systems involved, as detailed below. We present below (§4.2) two possible scenarios to account for the empirical facts, without favoring either. The empirical evidence can be summarized in four items:

[CII]/AFE has a small dispersion for R(60/100)< 0.6, $\sigma \sim 0.16$ dex.
[CII]/FIR has a moderate dispersion for $R(60/100) < 0.6$, $\sigma \sim 0.18$ dex, and falls off by an order of magnitude at larger $R(60/100)$ values (Malhotra et al. 2000a).

[OI]/FIR has a larger dispersion for $R(60/100) < 0.6$, $\sigma \sim 0.20$ dex, and shows no convincing evidence of falling with $R(60/100)$; there are few data points at larger $R(60/100)$ values, but the dispersion appears to increase quickly.

[OI]/[CII] rises with $R(60/100)$ (Malhotra et al. 2000a).

4.1. Uncertainties

The exact composition of grains responsible for the spectral features in the mid-infrared is uncertain, but these features correspond to bending and stretching modes of C-C and C-H bonds in Aromatic hydrocarbons (Duley & Williams 1981). The AFE have often been attributed to PAHs (Léger & Puget 1984; Allamandola, Tielens & Barker 1985); we will adopt here the notation PAH to refer to the carriers of the AFE. It is also uncertain in what proportion ionized and neutral PAH might contribute to the emission, especially in light of recent ISO observations that show little change in mid-infrared spectral shapes as the far-ultraviolet flux ranges over $G_0 = 1 - 10^5$ (Uchida et al. 2000). These data appear to contradict laboratory studies which show significant changes in relative strengths of different features from ionized to neutral PAHs, with the ionized PAHs much stronger in the 5 to 9 $\mu$m range.

In view of these uncertainties, we cannot unambiguously associate AFE with a specific stage of the photoelectric process, even though the evidence in Figure 1 suggests that the AFE closely track the rate of photoelectron generation into the interstellar medium. For instance, Figure 1 might be easily understood if AFE derive predominantly from PAHs that have just been ionized and are decaying from an excited state, or predominantly from recombining PAHs, or from both in a roughly constant proportion. However, no such association can be established, and moreover excitation by non-ionizing photons cannot be ruled out (Uchida et al. 2000). Furthermore, there is currently no way to ascertain or constrain the ionization balance of the carrier population.

Additional uncertainty arises from the significant variations known to occur in the concentration of AFE carriers relative to large grains. Boulanger et al. (1990) studied the relative distribution of 12 and 100 $\mu$m IRAS emission in molecular clouds and concluded that the variations of $R(12/100)$ required the abundance of transiently heated grains, which are mostly PAHs, to vary relative to the large grain population. In particular, they observed a systematic decrease of $R(12/100)$ as the 100 $\mu$m brightness increased, which appears as
limb brightening of clouds in AFE with a greater contrast than explained by optical depth effects. They proposed that this abundance variation is related to the cycling of interstellar matter between gas phase and grain surfaces. On the other hand, the AFE contribution to the total dust luminosity from galaxies decreases as the heating increases (Helou, Ryter & Soifer 1992; Lu et al. 2000). This trend has been related to the destruction of AFE carriers in the most intense heating environments near and in H II regions, a claim that is supported by observations of the Milky Way and the Small Magellanic Cloud (Tran 1999, Contursi et al. 2000), but may be linked to the effect observed by Boulanger et al. (1990). These depletion trends must then be superposed on the trends of photoelectric yield with interstellar medium parameters, resulting in the empirical evidence summarized above and in Figure 1.

4.2. Possible Scenarios

The close association of [CII] with AFE is easy to interpret at low values of R(60/100), by assuming that [CII] represents the cooling of the gas, and AFE measures the heating by photoelectrons. However, at larger values of R(60/100), reflecting an enhanced $G_0/n$ (Malhotra et al. 2000a), this association becomes puzzling since [OI] overtakes [CII] in cooling luminosity, casting doubt on the argument that [CII]/AFE is constant because it is intimately tied to the photoelectric effect. As the heating becomes more intense, the ratio of ([CII]+[OI])/AFE rises, suggesting an apparent increase in the photoelectric efficiency of the PAHs; this however is in direct conflict with the physics, leading us to the conclusion that PAHs become less significant contributors to the total photoelectric heating compared with other grain populations. This decreased significance is consistent with the decreased energetic importance of PAHs, manifested as the drop in AFE/FIR with increasing R(60/100) (Helou, Ryter & Soifer 1991).

In this picture of decreasing significance of [CII] as a cooling line and of AFE as a dust radiator, one would have to invoke a coincidental agreement between these two rates of decrease in order to explain the unchanged ratio of [CII]/AFE. This coincidence may reflect a certain scaling of $G_0$ with $n$, similar to the $G_0 \propto n^{1.4}$ derived by Malhotra et al. (2000a). Such a scaling might result from a feedback mechanism linking the density of the medium and the intensity of the star formation, turning the coincidence into a causal connection. In any case, it is not clear what drives the systematic decrease in AFE/FIR, though it has been suggested that a more intense radiation field may be inducing greater ionization or de-hydrogenation of the PAHs (Tielens et al. 1999).

An alternate scenario to explain the observations would be a two-component model
broadly similar to the Helou (1986) decomposition of the far-infrared emission into an "active" star formation component and a "quiescent" or cirrus component. The cirrus-like component would dominate at low values of R(60/100), and therefore be characterized by high values of [CII]/[OI], AFE/FIR and [CII]/FIR, just as one would expect from a photodissociation region with low density and $G_0/n$. On the other hand, the high-density photodissociation regions at the surface of molecular clouds directly illuminated by young massive stars would provide the active component, with elevated values of $G_0$, $n$ and $G_0/n$, resulting in more cooling via [OI] than [CII], and less efficient gas heating due to grain charging. In this scenario, one would have to assume that the AFE emission from the active component is depressed compared to the diffuse component, a property marginally suggested by the observations of lower AFE/FIR ratios in denser molecular clouds (Boulanger et al. 1996). A significant contribution to the active component by H II regions would also help explain the depressed values of AFE/FIR. The observed trends as a function of R(60/100) are then interpreted as a result of a varying proportion between the two components, with the interstellar medium falling almost bimodally into these two components, and the properties of each component varying little among galaxies.

While either one of these scenarios is plausible, each requires a number of assumptions which are difficult to verify with currently available data. This however illustrates the richness of the data at hand, and the need for a more sophisticated treatment of the interstellar medium on the scale of galaxies.

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Fig. 1.— The ratio [CII]/AFE is seen to be constant with FIR colors R(60/100) (top panel). This is in contrast to the ratio [CII]/FIR which declines for galaxies with higher R(60/100) colors, i.e. warmer dust (bottom panel). The constancy of [CII]/AFE suggests that the small grains which are responsible for mid-infrared emission also dominate the photoelectric heating of gas. The 1σ scatter is with respect to the mean ratio, which is indicated by the dotted lines in each panel.
Fig. 2.— The ratio ([CII]+[OI])/AFE is plotted against R(60/100). The scatter in the ([CII]+[OI])/AFE is larger than that for [CII]/AFE.