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Evolution of Dust Grains in Galaxies and HII/L2

By

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Abstract: The origin of interstellar dust grains is investigated based on the latest observations of the gas phase abundance and the features seen in the infrared spectra of various objects as well as in the diffuse galactic radiation. In contrast to the prediction by standard dust models, iron seems to remain mostly in solid phase even in the intercloud region, suggesting that the contribution from supernovae would be significant for iron-bearing interstellar grains. The 22 μm band detected in a supernova remnant, HII regions, and external galaxies, may be attributed to iron-bearing grains formed in supernova ejecta, though the identification of the band needs further investigation. Observations of the unidentified infrared (UIR) emission bands in the diffuse galactic radiation suggest that the band carriers should be formed in the interstellar space. Observations of the UIR bands in normal galaxies with various star-formation activities suggest that the *in situ* formation of the carriers in dense cloud regions is likely a dominant source for the band carriers, but there is some observational evidence that implies the formation in intercloud regions. Further studies are clearly needed to elucidate the origin and destruction of the carriers. Observations of dust properties in external galaxies are highly important to investigate the dust model since each dust component is supposed to have a different origin and evolution history, which should appear as variations in the infrared spectrum. A large-aperture cooled telescope, such as HII/L2, is strongly needed to pursue this kind of investigations and lead to the "unified dust model".

1. INTRODUCTION

The major constituents of interstellar dust grains have been considered to be silicate and carbon (cf. Mathis 1996; Li & Greenberg 1997), but the exact compositions of the grains are still far from complete understanding. A significant amount of new information on the dust grains has been provided by recent observations, particularly by space-borne cooled infrared facilities. Spectroscopic observations made by Infrared Telescope in Space (IRTS) (Murakami et al. 1996) and Infrared Space Observatory (ISO) (Kessler et al. 1996) have, in fact, shown the ubiquitous existence of very small carbonaceous grains in the interstellar space (Onaka 2000), leading to improved dust models including these new constituents (Désert et al. 1990; Dwek et al. 1997; Li & Greenberg 1997). ISO observations have also suggested the presence of other kinds of dust grains, which could be a major component in the interstellar space (cf. Chan & Onaka 2000).

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In order to study the compositions of interstellar dust grains it is quite important to understand where they are formed. Table 1 shows an estimate of the supply rates from various stellar sources according to Dwek (1998) together with the destruction rate of grains (Jones et al. 1996). For supernovae the supply rate indicates the ejection rate of the condensible elements, not the amount of dust grains formed in the ejecta since the efficiency of dust formation from supernovae is not yet fully understood. Thus the number should be regarded as an upper limit. According to Table 1, the destruction rate is much larger than the summation of the supply rates of all possible stellar sources. Significant processing of dust grains must be occurring in the interstellar space and a large fraction of the dust grains must thus be formed in the interstellar medium rather than being supplied from stellar sources. However, the variation of dust properties in various environments taking account of the dust processing has not yet been investigated in detail. Although very little is known of the dust properties in external galaxies at present, their characteristics should be quite interesting in this regard since galaxies provide quite different circumstances. The properties of dust grains there must be understood in the frame work of the "unified dust model", if any. Further, if the dust grains consist of several components, the evolution of the individual components may differ from each other in the galaxy evolution history (Dwek 1998). It is quite interesting to look for changes in the dust characteristics in remote galaxies. It is, however, still difficult to make spectroscopic observations of a star-forming galaxy similar to NGC6240 at $z > 1$ with the space infrared telescopes, such as SIRTF (Werner 1998) and ASTRO-F (Murakami 1998), to be launched in a few years from now. We badly need a large-aperture cooled telescope in space to pursue this kind of investigations.

Table 1: Dust budget in our Galaxy

	carbon	silicate	iron
	(10^{-6} $M_\odot$	kpc^{-2}	yr^{-1})
Stellar source			
C-rich giants	3	0	
M-rich giants	0	3.7	0.5
Type Ia supernovae	0.1	3.5	2
Type II supernovae	1.5	7	1
Destruction	40	80	

In this paper, I examine possible consequences of recent observations of the interstellar gas abundance in relation to the interstellar processing of dust grains and investigate the formation site of the dust components, suggesting new aspects of the interstellar grains based on the latest space infrared observations.

2. GAS PHASE ABUNDANCE

Figure 1 shows a compilation of the latest results of interstellar gas phase abundance for Mg and Fe against Si obtained by the Goddard High Resolution Spectrograph (GHRS) aboard HST (Savage & Sembach 1996; Fitzpatrick 1996, 1997, and references therein). The abundance of Mg has been all scaled based on the new oscillator strength (Fitzpatrick 1997; Sofia et al. 2000). Also plotted are the abundance for the solar and B star compositions, the latter being suggested to represent true interstellar elemental abundance in recent studies (Snow & Witt 1996). The change in the abundance is attributed to the change in the fraction of the element in dust grains. No matter which abundance (solar or B-star) is adopted as a reference, iron does not seem to return to the gas phase even when a large fraction of silicon is in the gas. Magnesium roughly follows silicon, but is slightly less released to gas than silicon. A recent observation by ISO also indicates a large fraction of silicon in the gas phase for the warm ionized medium (Mizutani et al. 2000). A study of the iron abundance in supernova remnants (SNRs) suggests that iron may not return to gas efficiently in the dust destruction process, supporting the GHRS results (Mouri & Taniguchi 2000).

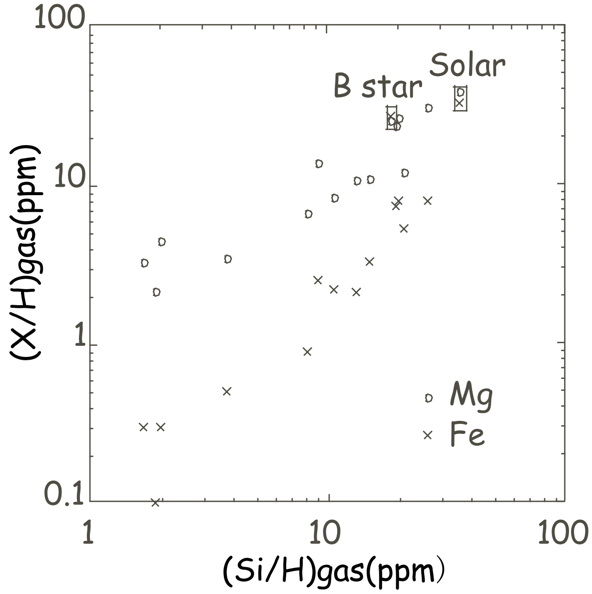

Fig. 1: Interstellar gas phase abundance obtained with the GHRS aboard HST. Circles indicate the amount of Mg in gas relative to H atom in units of 10^{-6} and crosses that of Fe against the Si gas abundance. The solar and B star compositions are indicated by rectangles.

On the other hand, no appreciable variation in carbon and oxygen abundance in the gas phase has been indicated by the GHRS observations over a wide range of gas density (Cardelli et al. 1996; Sofia et al. 1997). Carbon and oxygen are thought to be major constituents of the interstellar dust grains. These results are apparently not compatible with standard dust models, in which the major silicate grains are assumed in the form of (Mg, Fe)$_2$SiO$_4$. The results imply, instead, that iron, carbon, and oxygen reside in the refractory core of the grains and silicon in the volatile mantle. Recent investigations on the dust compositions have pointed out that some unknown mechanisms may be required to produce the observed abundance variation (Tielens 1998; Jones 2000). In the following sections I will investigate the origin of iron and carbonaceous grains based on the latest observations.

3. ORIGIN OF IRON GRAINS

The mass balance between the cloud and intercloud regions can lead to the following equation for the mass fraction of an element in dust grains, δ_c, δ_i, and δ_s, where the subscripts c, i, and s denote the cloud, intercloud, and stellar ejecta, respectively (e.g. McKee 1989):

$$M_i\delta_i \sim (\tau_d/\tau_a)M_c(1-\delta_c) + (\tau_d/\tau_i)M_c\delta_s, \tag{1}$$

where M_c and M_i are the total masses of an element in the cloud and intercloud regions, and τ_a, τ_d, and τ_i are the time scales of accretion, destruction, and injection from the stellar sources for dust grains, respectively. M_c and M_i are estimated to be about equal (Tielens 1998). In past studies the second term of the right hand side was assumed to be insignificant because a small value was expected for τ_d/τ_i according to Table 1. Dust grains were assumed to be formed in the cloud region by gas accretion and destroyed in the intercloud region by shocks. When δ_c is close to unity and δ_i is small, the equality can be satisfied if $\tau_d \sim \tau_a$ as theoretically estimated. However, if both δ_c and δ_i are close to unity as indicated for iron in Figure 1, τ_d/τ_a may have to be large. Since τ_a is simply determined by the impinging rate of the gas element, it is difficult to imagine a specific mechanism which can accelerate the accretion to the required degree. Therefore the large value of δ_i for iron implies that τ_d has to be larger than the theoretical estimate. This may be compatible with the observations of iron gas in SNRs (Mouri & Taniguchi 2000). If so, the second term cannot be neglected and the contribution from stellar sources may be significant for iron-bearing dust grains. According to Table 1, most iron-bearing grains in the interstellar space are expected to originate from supernovae.

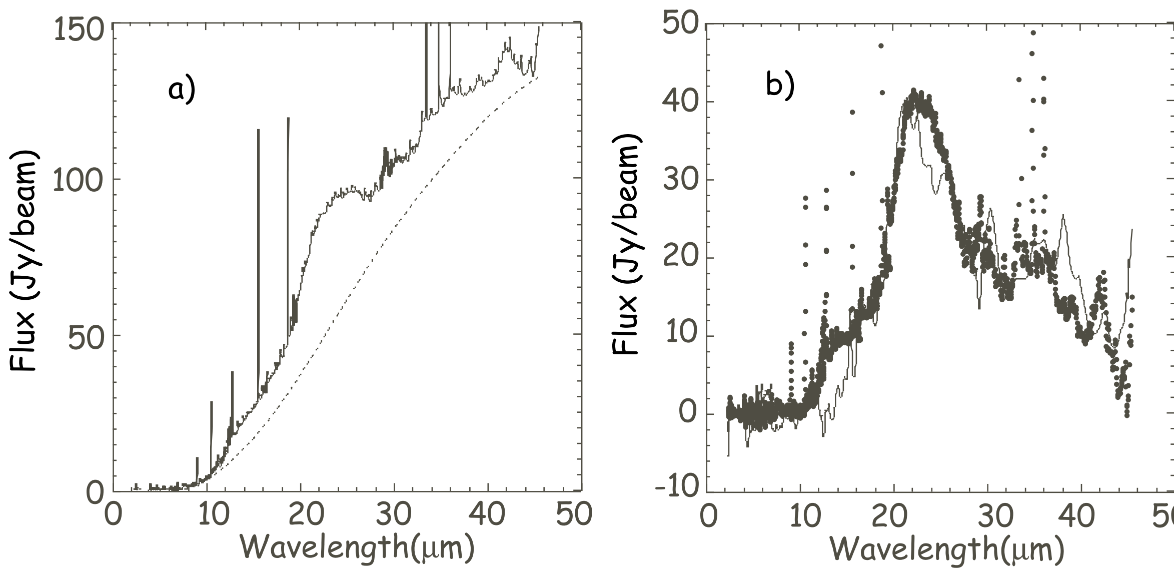

Fig. 2: (a) SWS spectrum of the Carina Nebula (solid line) and the assumed continuum (dashed line). (b) Comparison of the Cas A spectrum (solid line) to the 22 μm feature of the Carina nebula from which the assumed continuum has been subtracted (dots). See Chan and & Onaka (2000) for the detail.

The dust formation process in supernova ejecta is not yet completely understood, but several observations have indicated that the dust is indeed formed in the ejecta (see Dwek 1998 for more discussion). Very recently Arendt et al. (1999) have reported the detection of a new broad emission feature around 22 μm in an optical knot in the Cas A SNR with the short-wavelength spectrometer (SWS) aboard ISO, and attributed it to newly-formed dust grains in the knot. Chan & Onaka (2000) have found a very similar feature in the spectra of the Carina HII region. Figure 2 plots the SWS spectrum of the Carina region together with the comparison of the feature, from which the assumed continuum has been subtracted, to the Cas A spectrum. They have also pointed out the presence of the same feature in another HII region (M17: Jones et al. 1999) and galaxies, such as NGC7582 in which recent star formation was indicated, suggesting that the grains responsible for this feature may be a major member of the interstellar grains. The identification of the feature is not certain yet at present. Arendt et al. (1999) favored the identification with Mg protosilicate, but FeO grains also provide a similar good fit. Further investigations with SIRTF and ASTRO-F in various sources, including SNRs and galaxies, will definitely be needed to elucidate the nature of the grains and investigate whether they are indeed the iron-bearing grains formed in supernova ejecta or other kind of dust grains.

4. UNIDENTIFIED INFRARED BANDS AND CARBONACEOUS GRAINS

The unidentified infrared (UIR) bands are a family of the emission bands observed at 3.3, 6.2, 7.7, 8.6, and 11.2 μm in various objects. They are thought to come from very small carbonaceous grains with aromatic structures, but a definite identification of the material is still not established (see Tokunaga (1997) for a recent review). Recent observations by IRTS and ISO have shown that the UIR bands are present in the diffuse galactic radiation, clearly indicating that the band carriers are ubiquitous and must be a major component of the interstellar matter (Tanaka et al. 1996; Onaka et al. 1996; Mattila et al. 1996). Onaka (2000) has further shown that the band strengths are correlated linearly well with the far-infrared (FIR) intensity and the ratio of the 7.7 μm band strength to the FIR intensity is constant around 0.3 over a wide range of the strength of the incident radiation field (see also Onaka et al. 2000). The ratio indicates the relative emissivity and abundance of the band carriers to submicron dust grains. The good correlation suggests a well mixed population of the band carriers in the interstellar medium as well as a potential applicability of the ratio in investigations of the abundance and origin of the carriers.

Several mechanisms have been advanced for the formation of the carriers and three major formation sites have been investigated: mass-loss from AGB stars (Latter 1991), fragmentation of large carbon grains in diffuse cloud regions (Omont 1986; Jones et al. 1996; Greenberg et al. 2000), and *in situ* formation in dense clouds (Herbst 1991). The ubiquitous presence of the UIR bands in the interstellar space, even in the galactic center region where carbon-rich stars are rare (Onaka 2000), together with the small supply rate from mass-losing stars (Latter 1991; Greenberg et al. 2000), rules out the first possibility. The second possibility has so far been most frequently discussed. If this is the case, the mass ratio of the band carriers to the submicron grains can be written based on an equation similar to Equation (1) as

$$M_b/M_d \propto (\tau_a/\tau_d)(M_i/M_c), \tag{2}$$

where M_b and M_d are the total masses of the band carriers and submicron grains in a galaxy. The destruction rate τ_d depends on the supernova rate, while the accretion rate τ_a is related to the stellar birth rate. Both τ_d and τ_a have a similar dependency on the physical conditions in a simple model and may not vary among galaxies (Dwek 1998). The mass ratio M_i/M_c, however, may change with the activities of the galaxy in the way that more mass is associated with dense cloud regions in more active galaxies (cf. Negishi & Onaka 2000). Helou et al. (1991) have shown that the ratio of the IRAS 12 μm intensity to the FIR intensity decreases with the 60-to-100 μm color for infrared bright galaxies and the trend has been attributed to the decrease in the relative abundance of the carriers with the star formation activity in galaxies or to the destruction of the carriers under strong UV radiation fields. However, the continuum radiation longer than $12\,\mu$m could also contribute to the IRAS $12\,\mu$m and affect the $12\,\mu$m to the FIR intensity ratio (Daniel et al. 1999).

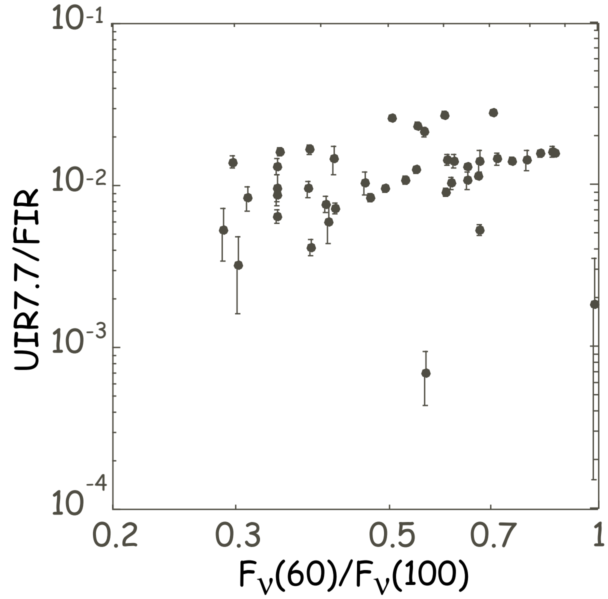

Fig. 3: The ratio of the UIR $7.7\,\mu$m band intensity to the far-infrared intensity for a sample of normal galaxies (Helou et al. 2000) against the IRAS 60-to-$100\,\mu$m intensity color.

Figure 3 shows a preliminary result of the ratio of the $7.7\,\mu$m band strength to the FIR intensity based on the ISO observations for a sample of normal galaxies (Helou et al. 2000) against the IRAS 60-to-100 μm intensity color. The 7.7 μm band intensity was derived from the PHT-S spectra, while the FIR intensity was estimated from the IRAS intensities (Helou et al. 1991). Dust extinction should be significant and its correction may be problematical for dusty objects. However, the 7.7 μm band is shown to be least affected by extinction (Lutz et al. 1998) and the $7.7\,\mu$m to FIR ratio may be a useful parameter to investigate the relative abundance of the band carriers. Figure 3 indicates that the ratio does not show a clear trend with the color, not directly confirming Equation (2). It should be noted that the ratio is very close to those found in the diffuse radiation of our Galaxy (Onaka 2000). The $12\,\mu$m flux to the FIR intensity of the same sample of galaxies shows a clear trend with the color similar to Helou et al. (1991), and therefore Figure 3 suggests that the contribution from the continuum of longer wavelengths is a dominant factor for the observed trend, while the UIR to FIR ratio does not change appreciably with the galaxy activities. A similar conclusion was also suggested by Lutz et al. (1998) in a study of starburst and ultra-luminous infrared galaxies (ULIRGs). The present results suggest a common origin for the band carriers and submicron dust grains and thus the *in situ* formation is likely to be a dominant source of the carriers. On the other hand, an increase of the UIR to FIR ratio has been observed in peripheral regions of dense clouds together with a decrease of the ratio in regions with large UV fields in several galactic objects (Onaka et al. 2000). The increase of the ratio may imply the formation of the carriers by fragmentation from large grains in diffuse clouds because such a process may occur more efficiently in interface regions, while the decrease suggests the destruction of the carriers under strong radiation fields. Further comprehensive studies are definitely needed to elucidate the the origin and processing of the band carriers. To investigate the variation in the relative abundance, comparison of the mid-infrared features with the FIR emission in a spatially resolved image would be most efficient. A large-aperture cooled telescope, such as HII/L2, would provide an unparalleled facility for the study of the origin of dust grains.

5. SUMMARY

The origin of the interstellar grains is still not understood clearly. Past studies have suggested that they are formed mostly in interstellar clouds rather than being supplied from stars. However, recent observations of the gas phase abundance indicate that iron grains may not be destroyed easily and thus the supply from stellar sources could be important for iron-bearing grains. The latest observations with ISO/SWS suggest that the dust grains emitting the 22 μm band are formed in supernova ejecta and they may be a major component of the interstellar grains. Whether they are iron-bearing grains or other kind of dust grains is not clear at this moment, though FeO grains have a band very similar to the observed feature. On the other hand, interstellar processing is suggested to be important for Si-bearing grains.

The observed good correlation between the UIR band and the FIR intensity suggests that the band carriers are likely to originate from the interstellar space. The present results of normal galaxies with different activities suggest that the *in situ* formation in dense clouds is a dominant source for the carriers, but there is also some observational evidence that implies the formation of the carriers by fragmentation from large grains. The formation and destruction process of the band carriers must be examined thoroughly in future studies.

Under any circumstance, it is quite interesting to investigate the relative abundance of dust grains with different origins. With this kind of investigations the formation and destruction processes of each dust component can be understood clearly and a better understanding of the properties of dust grains can be obtained. If iron-bearing grains and UIR band carriers have different origins from the submicron-sized grains as suggested in the present study, it would be most interesting to investigate the features from these grains relative to the FIR emission that comes from submicron grains in external galaxies with different physical conditions in their interstellar medium. Also important is the investigation of dust properties in remote galaxies since each dust component is supposed to have a different evolution history, which should appear as systematic variations in the infrared spectrum with the redshift or other age indicators of the galaxy.

SIRTF and ASTRO-F are expected to advance these studies significantly. However, even with them it is difficult to make spectroscopic observations of an active galaxy at $z > 1$. High spatial resolution observations in the FIR would also be quite important for detailed studies of the origin of each dust component. A large-aperture cooled telescope would provide an ideal facility. The understanding of dust properties in external galaxies is of high importance for the study of the evolution of galaxies and the universe because the effects of dust obscuration could be significant in distant objects and must properly be taken into account to correct them. The dust grains in galaxies must be understood consistently in the "unified dust model".

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