X-RAY HALOS AND LARGE GRAINS IN THE DIFFUSE INTERSTELLAR MEDIUM

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ABSTRACT

Recent observations with dust detectors on board the interplanetary spacecrafts Ulysses and Galileo have recorded a substantial flux of large interstellar grains with radii between 0.25 and 2.0 \mu m entering the solar system from the local interstellar cloud. The most commonly used interstellar grain size distribution is characterized by an \( a^{-3.5} \) power law in grain radii \( a \) and extends to a maximum grain radius of 0.25 \mu m. The extension of the interstellar grain size distribution to such large radii will have a major effect on the median grain size and on the amount of mass needed to be tied up in dust for a given visual optical depth. It is therefore important to investigate whether this population of larger dust particles prevails in the general interstellar medium or whether it is merely a local phenomenon. The presence of large interstellar grains can be inferred mainly from their effect on the intensity and radial profile of scattering halos around X-ray sources. In this Letter, we examine the grain size distribution that gives rise to the X-ray halo around Nova Cygni 1992. The results of our study confirm the need to extend the interstellar grain size distribution in the direction of this source to and possibly beyond 2 \mu m. The model that gives the best fit to the halo data is characterized by (1) a grain size distribution that follows an \( a^{-3.5} \) power law up to 0.50 \mu m, followed by an \( a^{-4.9} \) extension from 0.50 to 2.0 \mu m, and (2) silicate and graphite (carbon) dust-to-gas mass ratios of 0.0044 and 0.0022, respectively, consistent with solar abundance constraints. Additional observations of X-ray halos probing other spatial directions are badly needed to test the general validity of this result.

Subject headings: dust, extinction — ISM: abundances — scattering — X-rays: ISM

1. INTRODUCTION

Dust particle detectors on space probes currently exploring the outer solar system, e.g., Ulysses and Galileo, have provided direct evidence of interstellar grains entering the solar system on hyperbolic trajectories (Baguhl, Grün, & Landgraf 1996). The flow direction of these grains closely coincides with the flow direction of the neutral gas as determined by the Ulysses neutral gas experiment (Witte, Banaszkiewicz, & Rosenbauer 1996) and by observations of the backscattered He\(^{10}\) 584 \AA radiation (Flynn et al. 1998). These facts suggest that the detected grains are part of the interstellar dust population of the local interstellar cloud. An unexpected characteristic of the in situ–detected interstellar grains is that their inferred size distribution extends well beyond the maximum sizes usually adopted for interstellar grains (Landgraf et al. 2000). It must be noted that the dust detectors are able to record the mass, speed, and direction of incoming grains with radii above 0.05 \mu m, where the grain radii are inferred by assuming spherical shapes and a bulk density of 2.5 g cm\(^{-3}\) for the particles. Most of the mass of the observed grains is contained in particles with radii in excess of 0.35 \mu m and extending to 2.0 \mu m, while the maximum size of the commonly adopted Mathis, Rumpl, & Nordseteck (1977, hereafter MRN) size distribution for typical interstellar grains is 0.25 \mu m.

Frisch et al. (1999) compared the dust mass density contained in this extended grain size distribution with the gas mass density of the local interstellar gas and derived a local dust-to-gas mass ratio of \( R_{d/g} = 1.1^{+0.30}_{-0.35} \times 10^{-2} \). The local dust-to-gas mass ratio derived by Frisch et al. represents a lower limit since it has not been corrected for the missing flux of smaller grains filtered out by the heliopause, nor has it been corrected for the potential flux from still larger grains that are beyond the limit of detectability of the current detectors. Its value is about twice the canonical average Galactic value of 0.6 \times 10^{-2} (Spitzer 1978, p. 162), derived on the basis of an average UV extinction per kiloparsec and average gas densities, but comparable to 0.94 \times 10^{-2}, the total mass fraction of refractory elements present in a gas of solar system abundances.

Independent evidence for the existence of large interstellar grains in the size domain detected by Ulysses and Galileo is provided from the analysis of presolar grains in primitive meteorites (Anders & Zinner 1993; Amari, Lewis, & Anders 1994). Silicon carbide and graphite grains with isotopic compositions pointing toward a supernova origin are the dominant ones in the collection of large presolar grains. Theoretical calculations show that the radioactive environment of supernova ejecta leads preferentially to the formation of relatively large, i.e., micrometer-sized, grains (Clayton, Liu, & Dalgarno 1999). However, the total mass fraction of interstellar dust of supernova origin is not well known. If supernova condensates produce most of the silicates and a significant fraction of the interstellar carbon dust (Dwek 1998), then large interstellar grains may be prevalent in the general interstellar medium (ISM). Unfortunately, the present interplanetary dust detectors on board Ulysses and Galileo cannot provide any information on the chemical composition of the large grains to confirm these theoretical assertions.

In this Letter, we examine whether the population of large interstellar grains is only present in the local environment, because of some local spatial or temporal fluctuation in the grain size distribution, or whether this population is present in the general ISM. These large dust particles are gray at optical wavelengths, and therefore their existence could not be con-
strained by the extinction analysis of MRN. We show that the profile and intensity level of scattered X-ray halos are potentially the most sensitive indicator of the relative number of large grains along interstellar lines of sight (§ 2). In § 3, we use the X-ray halo of Nova Cygni 1992 and the \textit{Ulysses} and \textit{Galileo} constraints on the abundance and size distribution of large interstellar grains to study the grain size distribution along the Nova Cygni line of sight (§ 3). The results of our Letter and their astrophysical implications are discussed in § 4.

2. X-RAY HALOS AS TRACERS OF LARGE INTERSTELLAR GRAINS

Only a few of the observable interstellar dust characteristics show any specific sensitivity to the relative number of larger grains. These include the wavelength of peak linear interstellar polarization (e.g., Messinger, Whittet, & Roberge 1997), the dust albedo at near-infrared wavelengths (Kim, Martin, & Hendry 1994; Witt, Oliveri, & Schild 1990; Lehtinen & Mattila 1996; Witt et al. 1994), and the shape and intensity of X-ray halos surrounding point sources of X-rays (Mauche & Gorenstein 1986; Mathis & Lee 1991; Predehl & Klose 1996). Linear interstellar polarization is observed to peak at wavelengths in the visible or near-infrared along different lines of sight, and a close correlation between these peak wavelengths and the maximum size of the aligned grains is predicted by interstellar extinction models. Longer peak wavelengths are found mostly in denser clouds (Messinger et al. 1997), pointing toward larger grains there. However, for the wavelength of maximum polarization to be a unique indicator of maximum grain size, grains of all sizes must be aligned with equal efficiency in all environments, and grains of all sizes must be nonspherical to the same degree. Existing data, which relate the wavelength of maximum polarization and the ratio of total to selective extinction (an alignment-independent indicator of grain size), exhibit considerable scatter (Whittet 1992, p. 102; Martin, Clayton, & Wolff 1999). With the “alignability” of grains of different size remaining in question, interstellar polarization does not appear to be the most reliable indicator of grain size.

The dust albedo varies as $a^3$ for particles satisfying the condition that $2\pi a l / \lambda \ll 1$ (Bohren & Huffman 1983, p. 140). For the interstellar grains detected by \textit{Ulysses} and \textit{Galileo}, this wavelength region is in the near-infrared. Observations of high-albedo scattering at near-IR wavelengths (Lehtinen & Mattila 1996; Witt et al. 1994) have therefore been interpreted in terms of larger-than-average grain sizes. Unfortunately, only relatively dense dust structures have sufficient optical depth in the near-IR to produce easily measurable scattered light intensities, and, as a result, this method is not practical as a means to study the large end of the dust size distribution in the diffuse ISM.

The shape and intensity of X-ray halos surrounding X-ray point sources are strongly dependent on the largest grains along the line of sight (Catura 1983; Bode et al. 1985), providing the most promising method for probing the abundance of large grains in the general ISM. The efficiency for X-ray scattering varies approximately as $a^4$ (Catura 1983) while the differential cross section varies as $a^6$ (Hayakawa 1970). Therefore, for any typical size distribution $n(a) \sim a^{-p}$ with $3.0 < p < 3.5$, the largest grains will dominate the X-ray–scattering halo. Only in the weak outer parts of the predicted halos is the effect of smaller grains noticeable (Mathis & Lee 1991). The X-ray halo approach has the added advantage that typical Galactic sight lines with $N(H) \sim 10^{21}$ cm$^{-2}$ are sufficiently thin to the interaction of dust with X-rays so that single-scattering approaches are adequate, yet sufficiently long, to produce X-ray halos intense enough to be observable with current orbiting X-ray telescopes.

In the following sections, we will briefly review the available observational data for the sight line toward Nova Cygni 1992 and describe the dust models used to model the halo intensity and profile.

3. THE X-RAY HALO OF NOVA CYGNI 1992

3.1. Observational Data

The data for the X-ray intensity of the Nova Cygni 1992 halo have been taken from Mathis et al. (1995) and are based on a 2240 s integration with the \textit{ROSAT} Position Sensitive Proportional Counter taken on 1992 December 6, 291 days after outburst. We adopt as the hydrogen column density a value of $N(H) = 2.1 \times 10^{21}$ cm$^{-2}$, which is based on the mean interstellar reddening value $E(B-V) = 0.36 \pm 0.04$ determined for Nova Cygni 1992 by Austin et al. (1996). These values are about 50% higher than the corresponding values adopted by Mathis et al. (1995) and by Smith & Dwek (1998). We consider the Austin et al. (1996) reddening result to be more nearly definitive, given that it is based on an exhaustive study of all optical and UV extinction indicators available for Nova Cygni 1992. Since the derived hydrogen column density is reddening-based, we must consider the dust-to-gas mass ratio an adjustable parameter when we adopt a size distribution including larger grains because the larger grains contribute little reddening but considerable mass.

3.2. Adopted Dust Abundance and Size Distributions

In the computations for this Letter, we compare the scattering halos produced by three different grain size distributions with observations. We also examine the effect of the spatial distribution of the dust along the line of sight on the halo.

We assumed that all the interstellar silicate, magnesium, and iron are locked up in silicate dust particles with a total atomic weight of 172 amu (Si + Mg + Fe + 4x O) and a mass density of 3.3 g cm$^{-3}$. For gas with solar abundances, the resulting silicate-to-hydrogen mass ratio is 0.0062. We assumed that 270 carbon per 10$^3$ H atoms are incorporated into the dust. With a graphite mass density of 2.2 g cm$^{-3}$, the resulting graphite-to-hydrogen mass ratio is 0.0032. With an H/He number ratio of 10, the total dust-to-gas mass ratio is 0.0066, close to the canonical Galactic value of 0.006.

Three different grain size distributions, all normalized to the same dust-to-gas mass ratio, were used in the calculations. The first consisted of the standard MRN size distribution that follows an $a^{-3.5}$ power law in grain radii between $a_{\min} = 0.005$ μm and $a_{\max} = 0.25$ μm. The second grain size distribution was characterized by an $a^{-3}$ power law between 0.005 and 0.5 μm, followed by an $a^{-4}$ extension from 0.5 to 2.0 μm, as observed by Landgraf et al. (2000) for interstellar grains currently flowing through the solar system. We will refer to this modified MRN distribution as the XMRN distribution. As a third case, we adopted another modified MRN distribution, this one with the original values for the upper and lower size limits of $a_{\min} = 0.005$ μm and $a_{\max} = 0.25$ μm but with a less steep power law, namely, $a^{-3.5}$. This places a larger fraction of the mass into the larger grains without actually changing the range of the size distribution.

Two line-of-sight dust distributions were considered: a uniform distribution as adopted previously by Mathis et al. (1995)
and Smith & Dwek (1998) and a distribution in which the entire dust is contained in the last one-third of the 3.2 ± 0.5 kpc (Paresce 1994) optical path, closest to the Sun. We consider the latter distribution to be more realistic, given that the Galactic latitude of Nova Cygni 1992 of \( b = +7.8 \) places the source at a \( z \)-distance of about 450 pc, well above the average Galactic interstellar dust layer.

3.3. Halo Predictions

For the computation of the X-ray differential cross sections, we employed the Mie theory approach as suggested by Smith & Dwek (1998, 2000). This avoided the demonstrated shortcomings of the traditionally used Rayleigh-Gans approximation (Bohren & Huffman 1983, p. 158), which would have substantially overestimated the scattering cross sections for the energy of the observed X-rays of 0.4 keV (Mathis et al. 1995) and the larger grains in our adopted size distributions. The optical constants for the graphite and silicate grains were taken from Martin & Rouleau (1991) and Rouleau & Martin (1991). The Mie calculations were carried out with a code developed by Wiscombe (1979, 1980). The code was originally developed for the purpose of modeling the optical properties of aerosol particulates in the Earth’s atmosphere and is therefore particularly suited for cases in which the grain size parameter, \( \pi a/\lambda \), is significantly larger (maximum values up to 20,000) than unity. For calculating the halo intensity, we adopted a point-source flux of 6.62 \( \times \) 10\(^4\) counts at an energy of 0.4 keV (\( \lambda = 0.003 \mu m \)) and a hydrogen column density \( N(H) = 2.1 \times 10^{21} \) cm\(^{-2}\).

Figure 1 compares the calculated halo intensity and profile for the various cases with the observations. Four different model curves are shown in the figure. The standard MRN distribution (solid curve) for a uniform dust distribution along the entire line of sight leads to a predicted halo that is too bright by about a factor of 2, except in the innermost region. The lack of agreement with the data in the outer parts of the halo suggests that too much of the dust mass in this model is concentrated in the smaller grains that dominate the outer parts of the halo. Bode et al. (1985) noted a qualitatively similar disagreement between a predicted halo profile for an MRN-type distribution with a maximum grain radius of 0.2 \( \mu m \) and the observed halo of Cyg X-1 (image H821 in Bode et al. 1985). By contrast, the XMRN distribution for the uniform dust distribution (dotted curve) provides a much better fit. Most of the mass is now contained in the larger grains providing the large size extension, thus reducing the number of smaller grains. Consequently, the innermost part of the halo dominated by the largest grains is enhanced while the outer halo is correspondingly weakened, more nearly in agreement with the observations. The third size distribution tested (dashed curve), one with an MRN upper size limit of 0.25 \( \mu m \) but a less steep power law, exhibits a profile similar to that of the original MRN distribution (solid curve) but with overall larger intensities, resulting in an unacceptable fit. As the previous two, this halo also assumes a uniform dust distribution along the line of sight.

The fourth curve (dot-dashed curve) shows the predicted halo for the XMRN distribution for a line of sight in which all grains are concentrated in the last third of the light path closest to the observer. This curve demonstrates the fact that in addition to the largest grains, the grains closest to the source also add much power to the core of the scattering halo. By moving these grains closer to the observer, the central scattering peak loses power accordingly. This fit is qualitatively about as good as the fit of the XMRN curve with a uniform dust distribution. It could be improved by extending the size distribution to still larger sizes while keeping the dust-to-gas ratio constant at the original value of 0.0066. As demonstrated with the examples of the three uniform line-of-sight distributions (solid, dotted, and dashed curves), the addition of still larger grains would steepen the dot-dashed curve profile in the central core and lower the intensity in the outer halo, as required by the observations.

4. DISCUSSION

The results of our calculations show that extending the MRN grain size distribution to larger grain sizes, as characterized by the XMRN model, results in a better fit to the X-ray halo of Nova Cygni 1992. This suggests that particles with sizes larger than 0.25 \( \mu m \) constitute a significant mass fraction of the interstellar dust population along one line of sight through the general ISM. Our results are therefore the first extension of the conclusions of Frisch et al. (1999) beyond the local Galactic neighborhood of the solar system. However, in contrast to the locally based result of Frisch et al. (1999), we do not find any evidence that the dust-to-gas mass ratio along the Nova Cygni 1992 line of sight must be larger than the canonical interstellar value.

We need to examine to what extent our conclusions depend on the specific dust model used in the calculations. It is possible that other functional forms of the grain size distribution, different dust compositions or a different dust morphology, may provide an improved fit to the Nova Cygni 1992 halo.

There are currently a number of interstellar dust models that satisfy the usual observational constraints with different grain size distributions (MRN; Kim & Martin 1995; Weingartner & Draine 2001; Witt 2000). All size distributions have a large range of grain sizes; they are either continuous or in a multi-
mode distribution, and most of the mass is contained in the largest grains. No grain size distribution postulated for the diffuse ISM incorporates large grains in the numbers specified in § 3.2, and all would require similar modifications as we carried out with the MRN distribution in order to produce a satisfactory fit to the X-ray halo of Nova Cygni 1992. We conclude from this that our result is not a peculiar consequence of the assumed size distribution.

All models utilize similar amounts of the refractory elements (Snow & Witt 1995, 1996). The optical properties of the MRN model are determined by the assumed composition in terms of silicate and graphite grains with densities specified in § 3.2 and optical constants as given by Draine & Lee (1984). As shown by Mathis et al. (1995), adopting different compositions, especially for the carbonaceous component of the grains, as well as composite and porous structures instead of homogeneous, compact grains produces some variation in the overall halo intensity, but it does not significantly affect the profile shape. This was confirmed by the Mie calculations for porous particles by Smith & Dwek (1998) as well. We conclude from this that our result concerning the need for a grain size distribution extended to larger sizes is independent of the assumed composition, given the normal constraints, mainly from depletion studies and the study of grain band emissions and absorptions.

The presence of larger grains in our XMRN distribution beyond the MRN limit of 0.25 μm does not seem to impose an additional mass requirement beyond that set by the canonical Galactic dust-to-gas ratio, and thus our result does not further compound the problem of the apparent mismatch between the amounts of refractory elements required by grain models and the amounts of these elements available in the diffuse ISM, when recent depletion measurements and B-star reference abundances are combined (Snow & Witt 1996). On the other hand, it also does not solve this problem; it simply shifts more of the needed mass into larger grains. A full discussion of this problem goes beyond the scope of this Letter, and we refer to Frisch et al. (1999) for further details.

A serious problem does arise with respect to the XMRN distribution when one considers its impact on the wavelength dependence of extinction. The original MRN distribution was constructed with the constraint that the average Galactic extinction law with $R_V = 3.2$ as well as the canonical ratio of the extinction optical depth per hydrogen atom would be matched. By shifting most of the dust mass into grains with larger sizes, we find that the XMRN distribution leads to an extinction curve with $R_V = 6.1$ and an $A_v/N(H)$ ratio of only half the canonical value of $5.3 \times 10^{-22}$ cm$^2$. By contrast, the extinction for XMRN longward of 1 μm is greatly enhanced over that expected for the standard MRN distribution. The extinction law toward Nova Cygni 1992 is not known specifically, and a value of $R_V = 6.1$ would suggest a peculiar grain size distribution that differs from that in the average ISM toward that line of sight. A more likely solution to the present dilemma seems to be in the high probability that neither MRN nor XMRN, with their assumptions of chemically homogeneous, spherical solid particles, is the correct description of interstellar grains and their size distributions. The apparent incompatibility between the constraints arising from the X-ray halo of Nova Cygni 1992 and the Galactic extinction law simply illustrates again the incompleteness of current grain models (Witt 2000), which will not be resolved here.

We have demonstrated with the example of Nova Cygni 1992 that the line-of-sight density distribution of the scattering dust is also a critical factor in determining the shape of the scattering halo. We suggest, based on Nova Cygni 1992’s height above the Galactic plane, that a distribution with the dust concentrated nearer to the observer is a more likely one than a uniform distribution, but with the available data and only a single line of sight, this argument lacks power. It is therefore essential to acquire additional data of X-ray–scattering halo profiles of other point sources. Only when a representative sample of X-ray halo data yields results consistent with the present finding can the conclusions regarding the general existence of larger grains in the diffuse ISM be considered substantiated.

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