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Multiwavelength observations of interstellar dust

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Abstract. Interstellar dust is important in virtually every aspect of Galactic and extragalactic astronomy - whether one simply wants to correct for its effects or to study galactic dynamics and processes. Interstellar dust is found in every line of sight and is responsible for much of the radiation emitted by a galaxy. Multiwavelength studies of interstellar dust are critical to an understanding of the nature and evolution of interstellar dust. The dust absorbs strongly in the near and far ultraviolet where the stellar radiation field is most energetic and re-emits in the infrared. I will describe observations of interstellar dust ranging from the limited data sets in the UV and visible, where dust scattering and extinction are observed, to the all-sky survey data of IRAS and COBE. I will conclude with the importance of ASTROSAT to studies of interstellar dust.

Key words : UV radiation field, interstellar dust

1. Introduction

The diffuse ultraviolet radiation field was first studied 30 years ago (Weymann 1967) in the hope that emission from a wide variety of extragalactic sources would be detected. However, as in the infrared, actual observations soon revealed that the greatest part of this emission was actually due to Galactic processes, most notably starlight scattered from interstellar dust grains. Although detecting and characterizing the extragalactic emission remains the Holy Grail of background studies, the potential rewards from a thorough investigation of the diffuse ultraviolet background far exceed the original motivation.

Regrettably, the data have been of such poor quality that only a few and contradictory conclusions about the sources of the UV background have been drawn (reviewed in Bowyer 1991 and Henry 1991). The experimental situation has improved considerably in recent years, at least at shorter wavelengths (Murthy et al. 1999) but the modeling and interpretation of these data is still rife with uncertainties. We expect high quality data to come from the new generation of spacecraft, notably GALEX and ASTROSAT. Without a corresponding effort placed into the analysis of these data, the scientific return will be marginalized. The situation in the UV is analogous to that in the IR a few years ago. A treasure trove of high quality data became available after the IRAS and COBE missions, yet it is only in the last year that the tools to fully interpret these data have become available (e.g. Lagache et al. 1998, 1999).

In this work, rather than present another review of dust properties, which has been reviewed recently by Mathis (2000), I will describe a program that I have begun to model interstellar dust grains and their emission. In the following sections, I will describe the goals of this project and the method planned to bring it to realization.

2. Goals

The ultimate objective of this program is to further our understanding of the diffuse UV radiation field and of its sources. This is a complex problem but one which is tractable with a systematic approach. We will create a set of modules, each designed to address one part of the complete model. These modules will be self-contained, exportable programs upon which we can build further as the amount and quality of the data improves. Below we list our objectives for each of the individual models and in the following sections will describe them fully.

We will create a model of the interstellar radiation field as a function of the wavelength in the ultraviolet at any point in space. In practical terms, we are only interested in the ISRF within a few optical depths of the Sun, perhaps a volume of about 500 pc radius. Current models of the interstellar radiation field (e.g. Mathis, Mezger & Panagia 1993) do not account for the inhomogeneous distribution of the contributing stars and can yield intensities that are orders of magnitude off, particularly in the UV where the ISRF is dominated by a relatively small number of hot stars.

We will model the 3-dimensional distribution of the gas and dust in our galaxy with particular focus on the volume of space near the Sun where most of the UV emission arises. Recent observations from EUVE and GHRS (e.g. Dring 1997) can be combined with radio observations of CO emission (Dame et al. 1987) and HI (Stark et al. 1992) to map the ISM near the Sun.

We will create realistic models of the dust grains as a function of local environment. Using these models and using the results of the previous two steps, we will predict the level of emission from galactic dust over the entire sky. Our primary focus is in predicting the scattering in the ultraviolet; however, the energy not scattered by the grains must be reradiated in the IR and we also predict the IR radiation (e.g. Szomoru & Guhathakurta 1999).

We will use data currently available in the UV (see Murthy et al. 1999, Murthy & Henry 1995 for references) to confront our predictions and thus improve our models. We will have our models fully developed by the time the all-sky survey from GALEX becomes available. Through a thorough analysis of these data and ASTROSAT data to follow, we will probe the effects of different environments on the composition and size distribution of the dust grains.

We will use the models developed for our galaxy as templates for the interpretation of observations of the integrated emission of other galaxies. One of the prime goals for ASTROSAT is to obtain UV images of galaxies and clusters of galaxies. The emission in these objects is a complicated convolution of many different effects. Only in the Milky Way do we have sufficient information and resolution to separate these different contributions.

Once we understand the foreground emission from our own Galaxy, we will be able to explore the nature of the extragalactic radiation field. There are strong indications (Henry 1999) that there is a break in the extragalactic spectrum at 1216 Å fueling speculation that the extragalactic continuum is due to recombination radiation from an intergalactic medium.

3. The interstellar dust distribution

Scattering from interstellar dust is present in every line of sight, indeed dominating the diffuse radiation field in most directions. The first step in our model is to derive the dust distribution in each line of sight.

In our current model (Murthy & Henry 1995) we use the Bell Labs 21 cm survey (Stark et al. 1992) with the gas-to-dust ratio of Bohlin, Savage, & Drake (1978) to estimate the total amount of dust along the line of sight. We distribute this dust amongst the cells along the line of sight using an exponential falloff from the Galactic plane with a scale height of 200 pc, consistent with the results of Lockman, Hobbs & Shull (1986).

If the distribution of the dust is different from this ideal case, as it is almost over the entire sky, the amount of radiation emitted could vary considerably. As a simple example, if a dust cloud were to be located near a hot star, a reflection nebula would result with a brightness depending on the geometry between the cloud and the star. On the other hand, if the majority of the dust were far from the star, there would be no particular enhancement in the total amount of scattered radiation.

In order to have a truly realistic model of the diffuse light, we must incorporate the 3 dimensional distribution of dust in our Galaxy. In principle, a vast amount of information about the location and quality of the interstellar matter is available, from interstellar absorption measurements in the UV and visible to column density determinations from H I and CO in the radio; however, it is a daunting task to reduce these data to a unified model of our Galaxy. Fortunately, the scattered light in the UV largely arises in the immediate vicinity of the Sun (because of extinction in the Galactic plane and the rapidly declining radiation field and amount of matter in directions out of the plane) and our problem becomes more tractable.

As mentioned above, we currently use the 21 cm data along with a constant gas-to-dust ratio to derive a dust column density along any given line of sight. The infrared data are capable of probing column densities an order of magnitude lower than the H I data with the added advantage of measuring the dust emission directly without being subject to varying gas-to-dust rations (we now assume a constant gas-to-dust ratio everywhere). On the other hand, nonthermal emission from small grains and variations in the local heating significantly complicate the extraction of column densities. We will adopt an interactive procedure where we use modeling of the grain parameters and the interstellar radiation to predict the emission in the infrared. This will feed back into our dust distribution to create a self-consistent model for the dust distribution along the line of sight.

The IR and H I emission only provide information about the total amount of dust in any given direction, not about its location along the line of sight. Complementary information is provided by absorption line measurements of different ions which can actually place the dust at specific distances along the line of sight albeit with poor spatial resolution. Such a study was done by Dring (1997) who combined all published column densities with EUVE and GHRS data to derive the distribution of gas within 500 pc of the Sun. Note the presence of individual clouds; i.e., the gas is not smoothly distributed.

An old technique of mapping dust now achieving a new life is the use of extinction maps where a star field is mapped in several different colors. Such techniques, or the related technique of star counts, have been used to map the three dimensional distribution of dust in many regions of the sky such as the Coalsack (Franco 1995) or, recently, the molecular cloud IC 5146 at the sub-arcsecond level (Thoraval et al. 1997). There is a considerable amount of data now available from ground-based observations with modern large format CCDs (e.g. Szomoru & Guhathakurta 1999). Even more importantly, the Hipparcos mission mapped over a million stars with a high degree of photometric and positional accuracy, allowing interstellar dust clouds to be mapped with confidence (Knude & Hog 1998, 1999).

None of these data sets is adequate to sufficiently model the distribution of dust in our galaxy on their own. The global emission surveys in the radio and infrared only view the integrated column density, not its distance, while the extinction and absorption maps only probe the material to the particular stars being observed. Only through a detailed inspection of every line of sight will it be possible to build a self-consistent model of the matter in the galaxy. We will synthesize all of the data to yield our ultimate goal of a data cube of the dust (and gas) distribution within a few hundred parsecs of the Sun. We will proceed on a quadrant by quadrant basis, developing our techniques in areas where there is a superfluity of data and extending to less well-studied regions.

As soon as possible, we will make our model of the dust distribution available with the expectation that it will be of great utility in planning observations in the ultraviolet, specifically for ASTROSAT but also for other missions, current and planned.

4. The interstellar radiation field

In order to calculate the amount of starlight scattered from each cell, we must know the local radiation field; i.e., the radiation field at the point of scattering. In the UV, the interstellar radiation field (ISRF) is dominated by emission from a relatively small number of O and B stars and a catalog integration will yield a reasonable estimate of the sky brightness (Henry 1977).

In our current model, we use the SKYMAP star catalog (Version 3.3, Gottlieb 1978) as our source of stars. The location, brightness, spectral type, and distance of each star is tabulated in that catalog and, with the further assumptions of a uniform interstellar gas density and a standard extinction curve, we can calculate the vector ISRF (in the UV) at any point in space.

As an example of this procedure, and to test its fidelity, we have compared our prediction for the sky brightness at the Earth of direct (extincted) starlight at 1600 Å with that observed by the TD-1 satellite (Gondhalekhar 1990) at 1565 Å. The strongly anisotropic nature of the stellar radiation field is apparent, with Gould's belt (the projection of the local spiral arm on the sky) containing virtually all of the brightest sources. The ultraviolet sky is very patchy-much more so than the visible - with dark regions even in the Galactic plane. It is clear that no model which assumes a symmetrical source function can yield realistic predictions for the ISRF.

Our model also predicts the spectral shape of the radiation field at any point in space. As a test of our model, we have plotted its spectral shape at the Earth. Because we have little information on the gas and dust density, we assumed a uniform gas density of 1.2cm^{-3} (Spitzer 1978) and derived an extinction at every wavelength using the dust optical depth of Draine & Lee (1984). We have found good agreement with the levels observed by TD-1. The radiation field in the ultraviolet is dominated by a relatively small (20,000) O and B stars. Although the commonly used Mathis, Mezger & Panagia (1983) model gives results similar to ours in the near UV, where we both tied our models to the observed TD-1 values, they differ in the far-UV where there are no experimental checks. More importantly, the Mathis, Mezger & Panagia model is a gross misrepresentation of the overall radiation field which does not take into account the highly inhomogeneous nature of the ISRF in the UV.

Although SKYMAP contains much information about each star in its database, data from Hipparcos has shown that much of this information, particularly distances, is wrong. Where possible, we will switch our primary source of stellar information to the Hipparcos and Tycho catalogs, using SKYMAP only to provide additional information where needed. We note that although a model such as ours, where we take into account contributions from individual stars, is well-suited to predicting scattered light in the UV but cannot be used in the visible, where the ever increasing number of cool stars dominate the interstellar radiation field. If we hope to model the IR emission from the grains, we must take into account the contribution from late-type stars, which may be as much as half the total energy input into the grains (Trewhella et al. 1999).

We will use models of the star distribution in the visible (e.g. Cohen 1994, 1995) to populate each cell depending on its location in the Galaxy. We reiterate that, in the UV, there are few enough stars that we can place each star at its known position.

A knowledge of the local radiation field is crucial to understanding many astrophysical problems from the excitation of fluorescent H2 emission to the IR emission from dust. Although the radiation field of Mathis, Mezger & Panagia (1983) has often been used, it is, as we have shown, only a gross approximation to the true radiation field, which is strongly inhomogeneous and anisotropic. We will release our routines to calculate the ISRF at any point in space as soon as possible and will ensure that they are easy to use and portable.

5. Model improvements

As the amount of data available increases, our models must become increasingly more sophisticated to provide an adequate description of the data. The first version of our model (Murthy & Henry 1995) uses a dust distribution which is uniform over every line of sight. In addition, it employs an empirical dust model (that of Henyey & Greenstein 1941) with no dependence on local environment or, for that matter, on any physics at all.

The major improvements that we plan in this project are to : Synthesize a 3-dimensional model of the dust in the nearby interstellar medium from the multi-wavelength data publicly available. We will use this model both to predict the distribution of the dust along any line of sight and to calculate the extinction between any two points as required by our procedure to calculate the interstellar radiation field.

Use realistic models of the dust grains to predict the scattering and emissive properties of the interstellar dust. Replace our use of the outdated SKYMAP catalog with Hipparcos data. We will use models of the star distribution in our Galaxy to extend the ISRF into the visible.

Take into account multiple scattering. Gordon, Witt & Friedmann (1998) have shown that multiple scattering effects can be important in predicting the scattered emission. For instance, the albedo derived from a model assuming a homogeneous dust distribution will always be a lower limit on the true albedo (Witt & Gordon 1996). We already incorporate an inhomogeneous dust distribution in our model; we will add a Monte Carlo simulation of multiple scattering. We will also use the dust models to predict the thermal emission in the infrared. This will be compared with the all-sky maps of the sky from IRAS and COBE.

6. Testing the model

No model is of any utility without concrete testable predictions and our predictions are the intensity and spectrum of the diffuse radiation field over the entire sky. As discussed above, dust-scattered starlight is usually the largest component of this emission and we will be able to constrain the optical constants of the grains. The expected variation in the optical constants in different environments will feed back into our dust models. In selected directions and spectral regions, we will add other sources of emission such as an isotropic extragalactic background or line emission from the Galactic halo.

As an example of this procedure, we have used the first version of our model in an analysis of the few reliable observations of the diffuse ultraviolet radiation field in observed background intensities to study the optical constants of the grains, where we parametrized the grain scattering using the Henyey-Greenstein (1941) phase function. This is a purely mathematical function of two parameters characterizing the interstellar dust grains: the albedo (a) and phase function asymmetry factor ($g = \langle\cos\theta\rangle$). To this purely galactic component we added an isotropic extragalactic component (E) reddened by the total H I colum along the line of sight. Finally, we used a χ^2 analysis to place limits on the three parameters a, g and E. We obtained a reasonable fit for this limited set of data but the derived parameters depend heavily on the assumed values for the dust distribution. More data, of varying quality and sensitivity, have become available since that time from missions such as FAUST (Sasseen et al. 1995) and MSX (Mill et al. 1994) and we will certainly apply our model to those results. Although GALEX is not particularly suited for the study of the diffuse radiation field, we will be able to test our model with those data. A more complete test will come with ASTROSAT which will obtain a high resolution map of the diffuse radiation field.

There is much more data available in the spectral range between 912 and 1200 Å. We (Murthy et al. 1999) have reduced Voyager spectra of more than 400 locations spread out over the entire sky, observing a wide range of brightnesses; from many null detections to a peak brightness of almost 20 000 photons $\mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}\ \mathrm{Å}^{-1}$. Even more than the near UV, this spectral range is sensitive to details of the model, particularly the geometry of the stars and the dust. With the large number of directions observed, we will be able to test our model convincingly.

Although the scattered UV emission will be the primary focus of our proposal, there does exist a wealth of data in other wavelengths that must be used. For instance, the IR emission observed by IRAS and COBE is a direct measure of the albedo of the grains; the energy not scattered in the UV will be re-emitted in the IR. Using out models of the interstellar dust, we will calculate the heating due to the input stellar radiation and predict the emission in the IR, from the stochastic emission of small grains at 12 mm to the thermal emission from the cold dust population in the sub-mm. Such a study has been done by Sodroski et al. (1997) on a global scale, we will test our model on individual sightlines.

7. Conclusions

For more distant galaxies, characterizing the nature and effects of interstellar dust becomes significantly more difficult. Observational diagnostics now depend upon the use of surface photometry, where the effects of emission, extinction and scattering in the aperture must be disentangled. One approach has been to interpret the effects of dust in objects beyond the Local Group by assuming that all the extinction occurs in a single layer or screen of dust. Such a method produces color-excesses which appear to be simply correlated with an increasing optical depth of dust (i.e. less observed reddening means less dust). Unfortunately, circumstances are rarely that simple. The landmark work of Witt, Thronson & Capuano (1992) shows the screen paradigm to be simplistic, wrong, and often both. Specifically, scattering by dust grains can counteract the normal reddening effects of extinction. Thus, in effect, naive interpretation of broadband photometry can grossly underestimate the amount of dust present. This pitfall is clearly illustrated by Block et al. (1994), who demonstrate that use of the screen paradigm can lead to underestimating the dust by 90% !

Only in our own Galaxy do we have the spatial resolution necessary to completely deconvolve these different effects. Once we have developed and tested our models for the Milky Way, we will use them to interpret the observed emission from other galaxies; i.e., we will use our Galaxy as a template to understand the dynamics of radiation transfer in other galaxies.

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