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DIFFUSE GALACTIC RADIATION FROM DUST AND GAS: OBSERVATIONS AND MODELS

DIFFUSE GALACTIC LIGHT IN THE UV AND VISIBLE

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ABSTRACT. The diffuse galactic light, resulting from the coherent scattering of galactic starlight by dust grains contained in the general interstellar medium, has been the subject of active investigation for nearly 60 years. The separation of the diffuse galactic light from the other sources contributing to the light from the night sky has proven difficult, and different attempts at measuring the intensity and galactic distribution of the diffuse galactic light, both in the visible and the UV, are reviewed here. The interpretation of such measurements in terms of average scattering properties of interstellar grains is subject to additional uncertainties, stemming from the high degree of idealization imposed on the galaxy models used to study the radiative transfer problem. In the visible, the observations are more nearly definitive and the model problems less severe; reasonably consistent scattering properties have therefore been derived for this spectral region. In the UV, the situation is considerably less satisfactory, mainly due to a lack of sufficiently extensive, reliable measurements of the diffuse galactic light intensity at $\lambda < 200$ nm. A dedicated space mission may be the required solution. The radiative transfer in the UV presents serious difficulties due to the increasing opacity of the interstellar medium with shorter wavelengths and the resulting growing importance of the local galactic structure.

1. INTRODUCTION

1.1. Definitions

For the purpose of this review, I will use the term Diffuse Galactic Light (DGL) to denote the diffuse component of the galactic background radiation produced through coherent scattering of visible and UV photons by dust grains in interstellar space. The wavelength range covered for this discussion extends from about 100 nm to about 1000 nm. I mention in passing that other components of the diffuse galactic background exist in this same spectral region which have their origin in processes other than scattering, e.g., photoluminescence by dust in the 550–850 nm range, noncoherent fluorescence by molecular hydrogen at wavelengths $\lambda < 170$ nm, diffuse Hα emission, and resonance-line scattering by abundant interstellar atomic or ionic species mainly in the UV. Some of these processes will be covered elsewhere in this volume. The spectral nature of the DGL is that of a continuum, reflecting to first order the energy distribution of the interstellar radiation field in the visible and UV. As a component of the integrated light from the Milky Way, DGL contributes approximately 25% of the total; the remainder is direct starlight.

1.2. Historical Background

The history of DGL studies is best divided into two periods. The first extends from the initial discovery of the DGL in the 1930's to about 1967, when the very existence of DGL was again questioned. The second period covers the confirmation of the reality of the DGL and includes the studies of the DGL in the UV. This interesting history reflects the considerable difficulties

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encountered in observing the DGL.

Shortly after the demonstration of general interstellar extinction in the Galaxy by Trumpler (1930), Struve (1933) advanced the suggestion that DGL might be observable at low galactic latitudes. While attempting to measure the surface brightness of galactic dark nebulae, Struve and Elvey (1936) discovered that the intensity of the nebular light and that of the surrounding sky at low galactic latitudes were almost identical. They correctly interpreted this result as indicating one of two possibilities: either the particles in dark nebulae do not scatter at all or the interstellar space surrounding the dark nebulae contains a diffuse radiation field with an intensity essentially matching that of distinct clouds. Indeed, Wang (1935, 1936) had completed model calculations, based on scatterers with unit albedo and an isotropic phase function, which predicted DGL to amount to 33% of the total integrated light from the Milky Way.

Elvey and Roach (1937) conducted the first photoelectric all-sky photometric survey that yielded the initial direct detection of the DGL at visible wavelengths. Their observational approach also defined one of the two basic methods of DGL observation: an all-inclusive sky photometry with a wide-field (9 deg^2) photometer, with subsequent subtraction of major individual components contributing to the light from the night sky: permanent airglow, atmospheric scattering, zodiacal light, and direct starlight. Elvey and Roach reported a positive residual intensity, confined mainly to the band of the Milky Way and in approximate agreement with Wang's prediction, which they interpreted as DGL. The largest uncertainty in their result, by far, was due to the limited information about the direct starlight, which was deduced from star counts covering only a very small fraction of the total sky.

The important investigation by Henyey and Greenstein (1941) overcame this limitation posed by the poorly known direct starlight by introducing, for the first time, the use of a small-field photometer for DGL observation. Their Fabry-photometer, coupled to the 40-inch Yerkes refractor, permitted the detailed study of circular fields of 126″ diameter, which could be chosen for instance to avoid stars with $m < 16$. This eliminated the major source of contamination and of uncertainty stemming from the bulk of the direct starlight. The observations were limited to two sections of the Milky Way, the Cygnus and Taurus-Auriga regions, which were chosen to yield sky brightness data for $-30° < b < 30°$ while allowing the photometry to be carried out at constant zenith distances, thus keeping the atmospheric light components constant.

The resulting DGL intensities were in fair agreement with the values of Elvey and Roach for the same regions. The DGL intensity in Cygnus was found to be about twice that in Taurus-Auriga, roughly in similar proportion to the ratio of the integrated starlight from those two directions. This could be viewed as direct evidence for the forward-scattering nature of interstellar grains. For this reason, Henyey and Greenstein introduced the concept of non-conservative scatterers with an asymmetric phase function into the analysis of their DGL observations. They concluded from their data that the dust albedo, a, was in the range $0.3 < a < 0.8$, while the phase function asymmetry parameter, g, was found to be > 0.65. The parameter g is defined as the average of the cosine of the scattering angle α over the scattering function $\phi(\alpha)$; and $g > 0.65$ denotes a strongly forward-throwing pattern. The Henyey-Greenstein results are important historically, because, in spite of extensive efforts, only minor improvements have been achieved in our knowledge of the average dust scattering properties in the visible since the completion of their work.

The early 1960's returned the study of DGL to a state of confusion, when the new photoelectric all-sky photometric survey of Elsässer and Haug (1960) appeared to indicate little room for the existence of DGL. Several comparisons of the new Elsässer and Haug data with existing star counts by van Houten (1961), Roach and Megill (1961), and Megill and Roach

(1961) suggested that the integrated starlight alone could more than account for all the observed intensity ascribed to the galactic component. Indeed, the residuals at low galactic latitudes were generally negative, suggesting the existence of systematic errors somewhere within the data used in the analysis. In reviewing previous DGL work, van Houten (1967) concluded that there was no convincing evidence for the existence of DGL, supporting an earlier similar conclusion by Roach and Smith (1964).

2. MODERN OBSERVATIONS OF THE DGL

In this section, I briefly summarize observations which established the existence of DGL by observations with modern means, in the visible and the UV, from observing locations both on the ground and in space. I will refer to observing techniques employing the method of Elvey and Roach (1937) with degree-sized fields-of-view ($\sim 10^{-3}$ sr) as the large-field technique; the method of Henyey and Greenstein (1941) relying on observing minute-sized fields-of-view ($\sim 10^{-7}$ sr) will be referred to as the small-field technique.

2.1. Observations in the Visible

2.1.1. Ground observations. The small-field technique is the method of choice for DGL observation, provided light-gathering power is not a limiting factor. Using the 2.1m and 0.9m telescopes at the McDonald Observatory, Witt (1968) repeated the observations of Henyey and Greenstein with a number of improvements. The field was limited to 67″ diameter, and positions preselected on the *Palomar Observatory Sky Survey* were free of stars with $m < 20$. A photoelectric photometer was used and observations were done in the Johnson B and U filters, as well as in a narrow red band (27.5 nm FWHM) centered on the wavelength 610 nm. These measurements showed a clear excess intensity due to DGL in all three filters in both the Cygnus and Taurus-Auriga regions of the Milky Way. The DGL intensity was measured relative to a zero reference level at $|b| \sim 27°$ and therefore represented only a lower limit to the true absolute intensity. Witt's Cygnus observations were repeated by Roach et al. (1972; see also Roach and Gordon (1973) for a detailed discussion), using a small-field fixed-telescope technique. The agreement between the two sets of data was excellent.

As shown by Struve and Elvey (1936), the surface brightness of individual dark nebulae is closely related to the diffuse galactic light. Mattila (1970a) carried out surface photometry on two dark nebula complexes, the Southern Coalsack near $b = 0°$ and Lynds 1778/1780 in Libra near $b = +37°$. These two lines of sight offered the combined advantages of low star background and large optical depth for efficient scattering, while providing for substantially different illumination geometries. Again, the agreement between the diffuse light intensities as well as the colors found for the Southern Coalsack and the equally optically thick region near $b = 0°$ in Cygnus observed by Witt were very good. In conclusion, the existence of DGL at an average level of about 25% of the line of sight starlight at visible wavelengths is now a well-established fact.

2.1.2. Space observations. Some astronomical space experiments of the recent past had the capability to carry out photometry of the sky in the visible, suitable for DGL studies: the Wisconsin Experiment Package (WEP) on the Orbiting Astronomical Observatory-2 (OAO-2), and the Imaging Photopolarimeter (IPP) on the Pioneer 10 deep space probe.

The instrumentation and operation of WEP have been described in detail by Code et al. (1970). The capability in the visible consisted of pointed observations with a 10′ circular field-of-view, with a filter pass band centered at 425 nm (86 nm FWHM), through a 200 mm aperture telescope. The principal advantage of orbital observations in the visible is the avoidance of airglow and other atmospheric effects, which was assured by the 880 km altitude of OAO's orbit.

Witt and Lillie (1973) used this configuration for pointed observations of 29 of Kapteyn's Selected Areas, spanning the range of galactic latitudes $-86° < b < +86°$. Detailed star counts existed for the target areas, as did photoelectric photometric data for the typically 9th magnitude central stars of the fields, so that corrections for direct starlight could be derived. Corrections for zodiacal light were taken from the study of Lillie (1972). Positive residuals were detected in most target regions, yielding an estimated DGL intensity comparable to that found in groundbased programs. A major source of uncertainty of this first OAO-2 program was the relatively large size of the starlight corrections.

A significant improvement was achieved by Lillie and Witt (1976), who used the same instrument to observe the sky in 71 fields in which stars were generally fainter than $m_{pg} = 11.5$, leading to much lower corrections for direct starlight. Observations in the galactic longitude range $65° < l < 135°$ produced evidence for DGL of $47 \pm 13 S_{10}(\lambda)$ at 425 nm near the galactic equator, with lower intensities at higher galactic latitudes.

The IPP on Pioneer 10 was equipped with a 25 mm telescope and two-channel photometer with blue (λ_c = 440 nm, 90 nm FWHM) and red (λ_c = 635 nm, 90 nm FWHM) wavelength bandpasses. The instantaneous field-of-view of the spinning instrument (12.5 s period) was about 2°.3. The principal advantage offered by the Pioneer 10 instrument was all-sky photometric coverage from locations with heliocentric distances of 3AU and greater, where contributions from zodiacal light are negligible in the antisolar hemisphere. Toller (1981) conducted a very careful analysis of the Pioneer 10 data. This included a determination of the DGL for the blue bandpass by subtracting a direct starlight component derived from existing star counts. The resulting DGL values show a somewhat steeper concentration toward the galactic plane than does the direct starlight, so that the ratio of DGL to line-of-sight starlight varies from near 0.35 at $b \sim 10°$ to 0.15 near $b = 80°$. At the galactic equator this ratio is near 0.20. Toller also demonstrated a well defined correlation between DGL intensities at $|b| > 10°$ and the integrated H I column densities of Heiles (1975):

$$DGL\,(S_{10}(V)_{A_0V}) = 1.3\times10^{-20} N_{HI}\,\mathrm{atoms}^{-1}\mathrm{cm}^{2}. \qquad (1)$$

The Pioneer 10 data base still offers important opportunities for the future. It is now technically feasible to automatically scan photographic plates and to derive accurate photometric and positional information on stars as faint as 19th magnitude. The effort currently underway at the University of Minnesota to scan the plates of the Palomar Sky Survey, for example, promises to provide a photometric catalog of about 10^9 stars in the near future (Pennington, Humphreys and Ghigo 1988). Integration of such a catalog will provide an excellent source of direct starlight information, allowing a still more productive analysis of the Pioneer 10 data.

2.2. DGL Observations in the UV

UV observations of the DGL have suffered from the lack of optically fast, large-aperture instruments operating beyond the Earth's atmosphere. Hence, observations of the sky background at wavelengths $\lambda < 320$ nm have been done mainly with medium to large field-of-view instruments. Fortunately, the direct starlight contribution in the UV is due to stars with brighter apparent magnitudes on average than is the case in the visible. A field-of-view for UV observations, therefore, does not need to be so small as to avoid a significant starlight contribution. An added benefit is the decreasing importance of the zodiacal light with shorter wavelengths.

In this section I shall review only those investigations which had as their major goal the study of the DGL at low and intermediate galactic latitudes, with the derivation of dust scattering properties as a principal aim. UV observations concentrating on high-galactic latitude fields, while having important DGL implications, will be reviewed elsewhere in this volume.

A first indication that DGL is an important component of the UV sky background was provided by the analysis of rocket data (Yamashita 1968) covering the range of galactic latitudes $0° < b < 40°$ in the wavelength range 135 nm to 148 nm (Hayakawa, Yamashita and Yoshioka 1969). Subsequent reinterpretations of these data by Rozkovskij and Matjagin (1971) and by Yoshioka (1972) did not result in a clear separation of the DGL component, suggesting the need for additional measurements.

The moderately sized (10′ diameter) fields-of-view of the four stellar photometers on board of the OAO-2 satellite, covering the 150 nm to 425 nm spectral range with ten filters, offered a unique opportunity to measure the DGL throughout the UV without significant interference from direct starlight. In two separate studies (Witt and Lillie 1973; Lillie and Witt 1976) the DGL was observed in 100 fields altogether. In the wavelength range 332 nm to 290 nm and at λ 155 nm, the ratio of DGL to line-of-sight starlight was found to be approximately 0.4 ± 0.1, while a lower value of this ratio, $0.25 \pm .05$, was found for the 250 nm to 190 nm region. The data suggest a slight decrease of these ratios with increasing galactic latitude, but this conclusion is subject to uncertainties stemming from the model used to transform the visible direct starlight into corresponding UV intensities. If one compares predictions from such a model with the empirically determined galactic latitude dependence of the UV galactic radiation field (e.g., Gondhalekar, Phillips, and Wilson 1980; Henry, Anderson, and Fastie 1980), one finds that the actual radiation field has a steeper latitude dependence than the models predict. This suggests that the ratio of DGL to actual line-of-sight starlight in the UV may, in fact, be constant with galactic latitude.

Important independent confirmation of the OAO-2 results came from the S2/68 UV telescope on the TD-1 satellite. Morgan, Nandy and Thompson (1976, 1978) derived DGL intensities at 274, 235, 195 and 155 nm for $0° < |b| < 30°$ by correcting sky background measurements for the contributions from unresolved stars, zodiacal light, and residual airglow. The TD-1 results are in excellent agreement with the OAO-2 data for the 195, 235, and 274 nm bands. In particular, they also show the decline in the relative DGL brightness at 235 and 195 nm compared to the higher DGL level at 274 nm. This decline is usually interpreted as indicative of an absorption nature for the 220 nm feature in the galactic UV extinction curve.

Differences of more than a factor two are apparent for the DGL intensities at 155 nm, with OAO-2 yielding the higher values. This discrepancy can be explained in part by the now well-understood difference in the absolute calibration of the two instruments, (Bohlin et al. 1980), which, for equal intensities, would yield an excess of 25% in OAO-2 over TD-1 at 155 nm. Also, the galactic longitude range covered in the two separate surveys was not the same.

Some of the far-UV background experiments at high galactic latitudes (e.g., Maucherat-Joubert, Cruvellier and Deharveng 1978; Paresce et al. 1979; Zvereva et al. 1981, 1982; Henry 1981; Joubert et al. 1983) extend their coverage to sufficiently low galactic latitudes to overlap with the OAO-2 and the TD-1 observations of the DGL. Their fields-of-view, however, are significantly larger than those of the latter two, and corrections for unresolved stars at low latitudes become a grave problem. Hence, their contribution to the study of the DGL near the galactic equator is quite limited. They do, however, provide quite consistent correlations between the diffuse background intensity in the far UV and the H I column density (e.g., Zvereva et al. 1982), demonstrating that even at high galactic latitudes the DGL is a significant component of the observed background.

Some of the more recent UV observations of the DGL are discussed elsewhere in this volume. Fix, Craven, and Frank (1989) report measurements of the background intensity, made at 150 nm wavelength along two great circles around the sky, with the Dynamics Explorer 1 satellite. The galactic latitude range $0° < |b| < 62°$ was covered. A positive correlation between the DGL intensity at high latitudes ($30° < |b| < 62°$) and the H I column density, as well as a steep increase in the measured background at $|b| < 20°$ to values near 5000 photons $cm^{-2}s^{-1}Å^{-1}sr^{-1}$ support the interpretation that the measured radiation is predominantly galactic in nature, mostly due to scattering by dust. Again, uncertain corrections for faint stars included in the 0°32 field-of-view at the lowest galactic latitudes render the DGL estimates there unreliable.

The UVX experiment aboard the Space Shuttle Columbia (Jan. 1986) by the Johns Hopkins University (Henry, Murthy and Feldman 1989, this volume) and the Berkeley Space Sciences Laboratory (Hurwitz, Bowyer and Martin 1989, this volume) yielded background measurements for eight regions at different galactic latitudes, but did not provide the hoped-for resolution of the basic question of the existence of a background -N(H I) correlation. The Berkeley data, covering the 142-184 nm range, characterized by smaller error bars, support such a correlation while the Johns Hopkins data do not.

Data which are still more spatially limited on the background in the Virgo Cluster region were presented by Onaka (1989, this volume; see also Onaka et al. 1989). The results from the UV imager (λ_{eff} = 156 nm, $\Delta\lambda$ = 30 nm) for the $60° < b < 80°$ region appear to be a consistent extension of the measurements reported by Fix, Craven and Frank (1989) for lower latitudes, and they suggest an isotropic UV background not associated with H I and presumably extragalactic in nature, of not more than 400 photons $cm^{-2}s^{-1}Å^{-1}sr^{-1}$.

Holberg (1989, this volume) reported the only UV background data for the 91 to 120 nm wavelength region, relying on Voyager 2 spectrometer observations with a 0°.1 × 0°.87 field-of-view. While most of the data consist of significant upper limits of about 100 photons $cm^{-1}s^{-1}Å^{-1}sr^{-1}$ for the high-latitude background in this wavelength region, an actual measurement of the diffuse background continuum in the low-latitude Ophiuchus region yielded a spectrum essentially identical to that of a moderately reddened O star. This suggests that dust scattering remains a major source of the background even in the far-UV. The average intensity of the Ophiuchus background was about 2000 photons $cm^{-1}s^{-1}Å^{-1}sr^{-1}$.

3. MODEL INTERPRETATIONS OF DGL DATA

The exterior motive behind DGL studies is the expectation that average scattering properties of interstellar grains may be derivable from the observed DGL intensities. Such empirically determined scattering parameters serve as important constraints for models of interstellar grains, and their knowledge is essential for realistic studies of interstellar radiative transfer, where interstellar dust is the primary source of continuous opacity in the UV and visible. It is from the comparison of such models with DGL observations that dust scattering properties are derived.

3.1. DGL Models

In DGL models two sets of characterizations are assumed, one to describe the dust scattering properties, the other to define the details of the dust and source distribution of the model in which the radiative transfer is studied.

A two-parameter description of the scattering properties of the dust in terms of the average albedo for single scattering and an average phase function asymmetry parameter is commonly used. The Henyey-Greenstein (1941) phase function is employed most frequently

$$\phi(\alpha) = \frac{1}{4\pi} \frac{1-g^2}{(1+g^2-2g\cos\alpha)^{3/2}}, \tag{2}$$

where the asymmetry parameter $g = \langle\cos\alpha\rangle$ varies between 0 and +1 to characterize cases ranging from isotropic scattering to complete forward scattering. Negative values of g representing preferred backscattering do not apply to particle sizes found among interstellar grains. The Henyey-Greenstein phase function and other similar analytical phase function expressions are reasonable first order approximations to actual scattering patterns likely to occur among interstellar grains. However, the actual scattering pattern may deviate from such analytical approximations for certain ranges of the scattering angle and, consequently, the same set of scattering particles may have to be characterized by apparently different values of g in different scattering geometries.

The geometric model for the radiative transfer must with reasonable accuracy represent the portion of the galactic disk within a few kpc from the sun, where the locally observable DGL originates. Given that the optical depth in the direction of the galactic plane is large, multiple scattering is an essential component of the transfer treatment. The first model, meeting these requirements, was worked out by van de Hulst and de Jong (1969). They adopted a uniform plane-parallel model with the sun located in the central plane. The source function was assumed constant throughout the disk, implying that the volume emissivity of stellar radiation and the local dust density depend on spatial coordinates, especially on the galactic z-distance, in the same manner. This assumption may represent the galactic conditions at visible wavelengths, where much of the starlight comes from A stars, actually rather well. This model to the interpretation of Witt's (1968) DGL observations was applied by van de Hulst and de Jong.

Bastiaansen and van de Hulst (1977), among others, recognized that a z-dependent source function may be required in other wavelength regions where the galactic z-distribution of the sources responsible for the illumination of the dust is noticeably different from that of the dust. They treated in detail the case where the source distribution was wider in z than the dust distribution. They found that if this geometry applied to a particular case, the model assuming a constant source function would have resulted in underestimates for the albedo and/or the phase function asymmetry factor, while both types of models would produce equally acceptable fits to existing DGL data.

Still more complex DGL models were studied by Mathis (1973) who, in an approximate manner, included the local spiral structure into his models as well as z-dependent source functions. Mathis stressed the need for absolute DGL intensity values instead of intensities above a reference level at $|b|$~30°, as obtained by Witt (1968). Relative DGL intensities near the galactic plane can be matched by a wide range of models depending on the assumed reference level at $|b|$~30° and independent determinations of albedo and phase function asymmetry are essentially impossible, according to Mathis.

Mathis' models (private communication) also allowed the computation of the expected DGL distribution for plane-parallel systems in which the distribution of stellar sources was more strongly confined to the galactic plane than the distribution of the dust. This case is most likely applicable in the UV, where O and B stars provide the bulk of the illumination. Compared with a model with a z-independent source function, this model produces higher albedo values and a lower asymmetry parameter when fitted to the same set of DGL observations.

Among the models discussed so far, none took into account the discrete cloud structure in the distribution of interstellar dust. This is probably the most serious deficiency of all continuous DGL models, as was demonstrated by Mattila (1971). He examined the production of DGL at the galactic equator in a galactic disk populated by both small ($\tau_v = 0.24$; 5 clouds/kpc) as well as large ($\tau_v = 1.5$; 0.5 clouds/kpc) clouds. This cloud structure, assumed to have the same overall extinction coefficient as equivalent continuous DGL models, is shown to have a significant effect upon the determination of the scattering properties of the dust contained within the clouds. Except for the limiting cases of unit and zero albedo, the albedo of a scattering cloud is always less than the single scattering albedo of an individual particle. Consequently, the DGL model with cloud structure will predict a substantially higher grain albedo than a corresponding uniform model would if matched against a given set of DGL observations. Mattila (1971) found albedo values greater by about 0.2 to 0.3 compared with van de Hulst and de Jong (1969) in fitting Witt's (1968) visible DGL values in the Cygnus and Taurus-Auriga regions. The effects of clouds must become still more important in the UV, where the optical depth per cloud is greater by a factor of two or three, and, consequently, where the volume of space involved in the locally observable DGL is correspondingly smaller.

In closely related work, Mattila (1970b), employing the Monte Carlo method for the multiple scattering treatment, pioneered the model calculation of the surface brightness of dark nebulae, assumed to be illuminated by the interstellar radiation field. He applied these models to his observations (Mattila 1970a) of the Southern Coalsack and of a high latitude dark nebula in Libra.

Witt and Stephens (1974) extended these calculations to include consideration of the surface brightness profiles of optically thick clouds. Detailed observations of such interstellar clouds can lead to well-determined scattering characteristics for interstellar grains (e.g., FitzGerald, Stephens and Witt 1976).

Finally, the scattering by high-galactic latitude, optically thin clouds was studied by Jura (1979) in an approximate manner. While extremely useful for estimating expected surface brightnesses at high b directions, Jura's expressions should be used only well within the limited parameter space, for which they were derived.

3.2. Additional Complications

DGL models generally assume the galactic plane to be a plane of symmetry, where the densities of sources and scatterers reach their maximum. Examination of the existing literature on the spatial distribution of the reddening material in the Galaxy (e.g., Pandey and Mahra 1987) reveals a number of additional complications. The scale height of dust varies by a factor of about four for different intervals of galactic longitude, and the galactic extinction coefficient varies with galactic longitude by about a factor of two. The maximum of the dust density is usually not found at z = 0 for most longitudes.

Such deviations from the assumed symmetry plane are also found for the distribution of sources, which is further complicated by its wavelength dependence. As observed by Henry et al. (1977) and by Gondhalekar, Phillips and Wilson (1980), the symmetry plane of the UV radiation field coincides with Gould's belt and is inclined by about 18° with respect to the galactic plane. It should be concluded from these facts that any DGL survey that is to be interpreted with idealized models must be extremely extensive and should cover as much of the entire sky as possible.

4. SOME RESULTS

4.1. Scattering Properties of Interstellar Grains

Not only is the observational determination of DGL intensities difficult, the interpretation of such observations with radiative transfer models is subject to equally large uncertainties. Results concerning scattering properties of interstellar grains derived from the DGL must therefore be treated with caution.

In the visible, where the observations are most complete and the interpretation possibly less complicated, there is reasonably close agreement on a value of 0.6 to 0.7 for the dust albedo and a phase function asymmetry factor of about 0.7, indicating strongly forward scattering grains. Also the most recent result of Toller (1981) of $a = 0.61 \pm 0.07$ and $g = 0.60 \pm 0.22$ is in line with this conclusion.

In the UV, the evidence is fairly strong for a somewhat reduced grain albedo near 220 nm wavelength, suggesting that the broad extinction hump near that wavelength is due to absorption. The observational evidence is also reasonably strong for significant dust scattering at still shorter UV wavelengths, but it is not certain whether the albedo reaches values much beyond 0.5. This uncertainty is still not resolved even with the analysis of the latest DGL measurements in this spectral region. Onaka's (1989, this volume) results at high latitudes, interpreted with Jura's (1979) model, yield the condition $a(1-g) = 0.065 \pm 0.015$. Fix et al. (1989) find that Jura's model, for any combination of a and g, does not provide a satisfactory fit to their data, but that regardless of model, the steep increase in DGL intensities at lower galactic latitudes requires a strongly forward-throwing phase function, i.e. they suggest $g >$ 0.9. With such a value and Onaka's condition, the albedo at far-UV wavelengths could indeed exceed 0.5.

This conclusion stands in stark contrast to the result of Hurwitz et al. (1989, this volume) who, from a careful analysis of the UVX experiment, conclude that the albedo is in the range 0.10 to 0.15, while the phase function asymmetry g is less than 0.2. These apparent contradictions are difficult to resolve as long as different experiments provide data on different, mostly very limited regions of the sky. Given that in the far-UV the illumination is due to a rather unsymmetric distribution of O and B stars and that the clumpy, irregular distribution of the local interstellar matter dominates the radiative transfer much more than at longer wavelengths, it is quite uncertain that a spatially limited set of observations represents an appropriate galactic average at all.

Further complicating factors and uncertainties come from the inadequacies of the various different radiative transfer models which were used in these analyses. Finally, the wide range of variations in the shapes of UV extinction curves observed by IUE (e.g., Witt, Bohlin and Stecher 1984) raises the question as to whether there is, in fact, a single representative set of scattering properties for the UV for interstellar dust, valid for all parts of the Galaxy.

4.2. Prospects for the Future

The prospects for solving the problems surrounding the observation of the DGL are quite good. In the visible, the combination of the integrated sky light data from Pioneer 10 obtained outside the zodiacal light belt with accurate counting and photometry of stars to V = 19 achieved with modern plate scanners will provide a major advance. This should yield extensive DGL data in the blue as well as the red spectral regions.

In the UV, the DGL as well as other sources of background radiation should be surveyed most directly with a dedicated space experiment from earth orbit. Such an experiment should have both photometric as well as spectroscopic capabilities with high diffuse-source sensitivity, such as, e.g., the proposed HUBE mission (Kimble, Henry and Paresce 1989, this volume). Very useful data, short of complete surveys, should already be expected from other instruments closer to flight, such as the UIT on the ASTRO mission scheduled for spring of 1990 or the FUVIS experiment (Carruthers et al. 1989).

REFERENCES

Bastiaansen, P. A., and van de Hulst, H. C. 1977, *Astr. Ap.*, **61**, 1.

Bohlin, R. C., Holm, A. V., Savage, B. D., Snijders, M. A. J., and Sparks, W. M. 1980, *Astr. Ap.*, **85**, 1.

Carruthers, G. R., Heckathorn, H. M., Dufour, R. J., Opal, C. B., Raymond, J. C., and Witt, A. N. 1988, *S.P.I.E.*, **932**, 87.

Code, A. D., Houck, T. E., McNall, J. F., Bless, R. C., and Lillie, C. F. 1970, *Ap. J.*, **161**, 377.

Elsässer, H. and Haug, U. 1960, *Z.f. Ap.*, **50**, 121.

Elvey, C. T. and Roach, F. E. 1937, *Ap. J.*, **85**, 213.

FitzGerald, M. P., Stephens, T. C., and Witt, A. N. 1976, *Ap. J.*, **208**, 709.

Fix, J. D., Craven, J. D., and Frank, L. A. 1989, *Ap. J.* (in press).

Gondhalekar, P. M., Phillips, A. P., and Wilson, R. 1980, *Astr. Ap.*, **85**, 272.

Hayakawa, S., Yamashita, K., and Yoshioka, S. 1969, *Ap. Space Sci.*, **5**, 493.

Heiles, C. 1975, *Astr. Ap. Suppl.*, **20**, 37.

Henry, R. C. 1981, *Ap. J.*, **244**, L69.

Henry, R. C., Anderson, R. C., and Fastie, W. G. 1980, *Ap. J.*, **239**, 859.

Henry, R. C., Murthy, J., and Feldman, P. D. 1989, in *Proc. IAU 139, Galactic and Extragalactic Background Radiation*, ed. S. Bowyer and Ch. Leinert (Dordrecht: Kluwer Academic Publsher).

Henry, R. C., Swandic, J. R., Shulman, S. D., and Fritz, G. 1977, *Ap. J.*, **212**, 707.

Henyey, L. G. and Greenstein, J. L. 1941, *Ap. J.*, **93**, 70.

Holberg, J. B. 1989, in *Proc. IAU 139, Galactic and Extragalactic Background Radiation*, ed. S. Bowyer and Ch. Leinert (Dordrecht: Kluwer Academic Publisher).

Hurwitz, M., Bowyer, S. and Martin, C. 1989, in *Proc. IAU 139, Galactic and Extragalactic Background Radiation*, ed. S. Bowyer and Ch. Leinert (Dordrecht: Kluwer Academic Publisher).

Joubert, M., Masnou, J. L., Lequeux, J., Deharveng, J. M., and Cruvellier, P. 1983, *Astr. Ap.*, **128**, 114.

Jura, M. 1979, *Ap. J.*, **227**, 798.

Kimble, R. A., Henry, R. C., and Paresce, F. 1989, in *Proc. IAU 139, Galactic and Extragalactic Background Radiation*, ed. S. Bowyer and Ch. Leinert (Dordrecht: Kluwer Academic Publisher).

Lillie, C. F. 1972, *The Scientific Results of the Orbiting Astronomical Observatory (OAO-2)*, ed. A. D. Code, NASA SP310, 91.

Lillie, C. F., and Witt, A. N. 1976, *Ap. J.*, **208**, 64.

Mathis, J. S. 1973, *Ap. J.*, **186**, 815.

Mattila, K. 1970a, *Astr. Ap.*, **8**, 273.

Mattila, K. 1970b, *Astr. Ap.*, **9**, 53.

Mattila, K. 1971, *Astr. Ap.*, **15**, 292.

Maucherat-Joubert, M., Cruvellier, P., and Deharveng, J. M. 1978, *Astr. Ap.*, **70**, 467.

Megill, L. R., and Roach, F. E. 1961, *Natl. Bur. Std. Tech. Note*, **106,** U.S. Dept. of Commerce, Office of Technical Services.

Morgan, D. H., Nandy, K., and Thompson, G. I. 1976, *M.N.R.A.S.*, **177**, 531.

Morgan, D. H., Nandy, K., and Thompson, G. I. 1978, *M.N.R.A.S.*, **185**, 371.

Onaka, T. 1989, in *Proc. IAU 139, Galactic and Extragalactic Background Radiation*, ed. S. Bowyer and Ch. Leinert (Dordrecht: Kluwer Academic Publisher).

Onaka, T., et al. 1989, *Ap. J.*, **342**, 238.

Pandey, A. K. and Mahra, H. S. 1987, *M.N.R.A.S.*, **226**, 635.

Paresce, F., Margon, B., Bowyer, S., and Lampton, M. 1979, *Ap. J.*, **230**, 304.

Pennington, R. L., Humphreys, R. M., and Ghigo, F. D. 1988, *Mapping the Sky*, S. Debarbat et al. (eds). (Dordrecht: Kluwer Acad. Publishers), 435.

Roach, F. E. 1967, *Modern Astrophysics, (Paris: Gauthiers-Villars)*, 49.

Roach, F. E. and Gordon, J. L. 1973, *The Light of the Night Sky* (Dordrecht: Reidel Publ. Comp) Chapter 5.

Roach, F. E. and Megill, L. R. 1961, *Ap. J.*, **133**, 228.

Roach, F. E. and Smith, L. L. 1964, *Natl. Bur. Std. Technical Note*, **214**.

Roach, F. E., Smith, L. L., Pfleiderer, J., Batishko, C., and Batishko, K. 1972, *Ap. J.*, **173**, 343.

Rozkovskij, D. A. and Matjagin, V. S. 1971, *Ap. Space Sci.*, **12**, 204.

Struve, O. 1933, *Ap. J.*, **77**, 153.

Struve, O., and Elvey, C. T. 1936, *Ap. J.*, **83**, 162.

Toller, G. N. 1981, *A Study of Galactic Light, Extragalactic Light and Galactic Structure using Pioneer 10 Observations of Background Star Light*, Ph.D. Thesis, State Univ. of New York at Stony Brook.

Trumpler, R. J. 1930, *Lick Obs. Bull.*, **14**, No. 420, 154.

van de Hulst, H. C. and de Jong, T. 1969, *Physica*, **41**, 151.

van Houten, C. J. 1961, *Bull. Astr. Inst. Netherl.*, **16**, 1.

van Houten, C. J. 1967, *Bull. Astr. Inst. Netherl.*, **19**, 303.

Wang, S.-K. 1935, *Compt. Rend.*, **201**, 1326.

Wang, S.-K. 1936, *Publ. Lyons Obs.*, **19**, 1.

Witt, A. N. 1968, *Ap. J.*, **152**, 59.

Witt, A. N., Bohlin, R. C., and Stecher, T. P. 1984, *Ap. J.*, **279**, 698.

Witt, A. N. and Lillie, C. F. 1973, *Astr. Ap.*, **25**, 397.

Witt, A. N. and Stephens, T. C. 1974, *Astr. J.*,
, 948.

Yamashita, K. 1968, *Ap. Space Sci.*, **2**, 4.

Yoshioka, S. 1972, *Ap. Space Sci.*, **16**, 421.

Zvereva, A. M., Severny, A. B., Granitzky, L. V., Hua, C. T., Cruvellier, P., and Courtes, G. 1982, *Astr. Ap.*, **116**, 312.

Zvereva, A. M., Severny, A. B., Hua, C. T., Cruvellier, P., and Courtes, G. 1981, *Adv. Space Res.*, **1**, 201.

G. Verschuur: Concerning the existence of diffuse emission from the galactic background, Edward Barnard makes mention of a residual glow that he saw in several regions. This may indicate that he was able to see light reflected from diffuse and widely spread dust which today is known as interstellar cirrus.

B. Wang: *What is standard theory modelling the asymmetry of the diffuse galactic light distribution with respect to galactic latitudes? Is there an alternative scenario?*

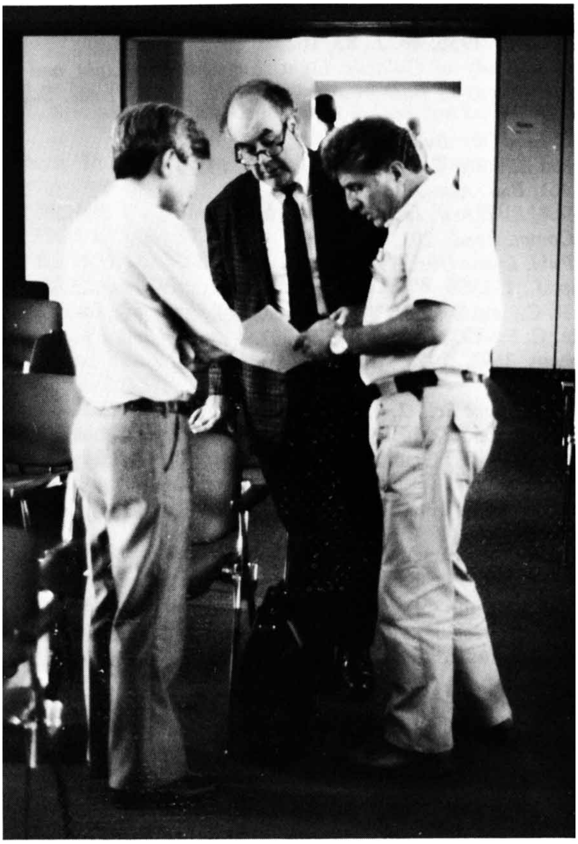
A.N. Witt: The standard models of diffuse galactic light assume a plane parallel geometry with the sun in the central plane. No asymmetry is predicted by such models. A more appropriate model would have to take into account the deviation of the sun's location out of the central plane as well as the observed asymmetries in the distributions of stars and dust. Such detailed models do not yet exist.

K. Mattila: *You did not mention any results for the far red and near infrared domain where scattering is still important. The reason is probably that there are no data?*

A. N. Witt: That is correct.

K. Seidensticker: *With respect to the large variations of interstellar extinction curves, especially in the UV, can we expect spatial variations of the scattering parameters a and g even in the visible spectral range?*

A.N. Witt: Yes, we can. Spectrophotometry of individual reflection nebulae and their illuminating stars in the visible provides strong indication for somewhat different wavelength dependencies of the dust albedo in different clouds. This kind of variation appears to be still more amplified in the UV. However, while there may not be a unique set of scattering properties, the diffuse galactic light approach, by integrating and averaging over long lines of sight, should at least provide an average set of dust properties.



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