THE GALACTIC FAR-UV BACKGROUND: CORRELATIONS WITH GAS AND DUST AT HIGH GALACTIC LATITUDES

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ABSTRACT. The correlations between the UV galactic background (after subtraction of direct starlight), the neutral hydrogen HI, the extinction and the 100 μm emission are discussed for high galactic latitudes mainly based on a new analysis of the D2B satellite data. While clear correlations exist between UV and the other quantities, indicating that most of the UV galactic background is starlight scattered by interstellar dust, these correlations are less tight than the correlation between HI and the 100 μm emission. Localized UV excesses are shown to exist and are due in some cases to 2-photon emission by ionized gas. The quantitative interpretation of the UV galactic background in terms of dust properties is discussed, and it is shown that both the galactic model and the clumpiness of interstellar radiation may affect the results considerably.

1. INTRODUCTION

The reviews by Boulanger, Bowyer, Paresce, and Witt (1989, this volume) have discussed various aspects of the galactic background emissions at high galactic latitudes and to some extent the relations between these emissions. The purpose of the present paper is to discuss more extensively these relations. Before going to the point, I find it useful to summarize some of the problems with the observations at large scales of the interesting quantities. Then I will discuss, mainly on the basis of a new analysis of the D2B satellite data, the correlations between the UV background, the neutral hydrogen and the far-IR radiation at 100 μm. I will show the existence of UV excesses with respect to the mean correlations and discuss their nature. Finally I will make remarks on the interpretation of these correlations.

2. OBSERVABLE QUANTITIES AND PROBLEMS

2.1. Atomic Hydrogen (HI)

There are a number of 21-cm line surveys covering very large fractions of the sky which can be used to infer the distribution of the column density of atomic hydrogen. These surveys suffer from differences in scale, but this can be taken into account when combining them together by matching the intensities in overlapping regions. For example, Boulanger and Pérault (1988) have constructed an all-sky map by combining the Berkeley, Argentina, and Parkes surveys. However, all the HI surveys are contaminated by stray radiation received by the antenna at large angles from the main beam (Lockman, Jahoda, and McCammon, 1986) with the notable exception of the Bell Laboratories survey (Stark et al., 1989). The latter survey has been made with the stray-radiation free horn antenna used by Penzias and Wilson for their discovery of the 2.7 K background radiation. This survey (Stark et al., 1989), which has a 2° angular resolution, must be used at high galactic latitudes. It gives intensities lower by a factor of about 2 when compared with the other surveys near the galactic poles. At galactic latitudes lower than 30–40° the combined survey and the Bell Laboratory surveys match

S. Bowyer and C. Leinert (eds.), The Galactic and Extragalactic Background Radiation, 185–192.

extremely well.

2.2. Interstellar Extinction

The extinction at high galactic latitudes can be obtained from photometry of individual objects (stars, globular clusters, galaxies and quasars) and also from star counts, but the only practical way of mapping extinction on very large areas is to count the surface density of galaxies as a function of apparent magnitude. This technique has been used extensively, but comparison with HI surveys reveals discrepancies with respect to the expected extinction assuming a constant reddening/HI (gas-to-dust) ratio E(B-V)/N(H). There are controversies as to the relative importance of the various factors which are responsible for these discrepancies (compare for example Burstein and Heiles, 1978, with Strong and Lebrun, 1982). These factors are:

1. zero level and stray radiation problems
2. irregularities in the distribution of galaxies
3. biases in galaxy counts (Lebrun, 1986)
4. presence of molecular gas
5. variable E(B-V)/N(H) ratio
6. cloud clumpiness (see Section 4).

Although the presence of molecular gas is directly established by CO observations in regions of apparent optical obscuration on the Palomar Sky Survey prints (Magnani, Blitz, and Mundy, 1985; see also Mebold et al., 1985) and by observations of the fluorescence of molecular hydrogen (Martin, Hurwitz, and Bowyer, 1989, this volume), the corresponding regions do not seem to cover large fractions of the sky at galactic latitudes larger than say 25 °. Thus factor (4) is not very important for our purpose. It seems that once factor (1) is eliminated factors (2), (3) and (5) are the most important, unfortunately in unknown proportions. I believe in particular that there are important variations in E(B-V)/N(H).

2.3. Far-infrared (FIR) Radiation

As discussed by Boulanger in this volume, the IRAS observations are little affected by zodiacal light at 100 and 60 μm. But zodiacal light is so intense at 25 and 12 μm that it cannot be subtracted at these wavelengths with an accuracy sufficient to get good values of the galactic background at high galactic latitudes. Striping and zero-level problems are of some importance, but in general the FIR fluxes at 100 and 60 μm should be accurate on properly-treated sky maps. The overall correlation of 100 μm fluxes with HI column densities is rather good (see Figure 5 of Boulanger and Pérault, 1988). However, one may expect FIR excesses with respect to the FIR/HII mean correlation in regions of higher-than-average interstellar radiation field (ISRF), and also due to the presence of dust associated with molecular hydrogen.

Indeed Désert, Basell, and Boulanger, (1988 and in preparation) have found molecular clouds by systematically studying the FIR excesses; however their contribution at high galactic latitudes is minor. The whole Gould Belt stands up in maps of the FIR excesses, certainly more due to a higher ISRF than to molecular gas.

2.4. Visible and Ultraviolet Light

The measurements of the diffuse galactic light in the visible and the ultraviolet have been extensively discussed elsewhere in this volume (see reviews by Bowyer, Paresce, and Witt, 1989, and the papers by Fix, Graven, and Frank; Guhathakurta and Tyson; Henry, Murthy, and Feldman; and Hurwitz, Bowyer, and Martin, all 1989, this volume). The difficulties with such measurements are well known: zero-level determination, airglow, zodiacal light and direct starlight. All these problems are more severe in the optical than in the far-UV, and this is why I will concentrate on the latter.

Early whole-sky measurements of the UV diffuse radiation have been performed by satellites (OAO2, TD1, ANS) designed for stellar studies. They had small entrance apertures, thus were relatively insensitive to diffuse light. This is also true for the IUE satellite. Diffuse-light studies with these satellites have been limited to bright objects and/or to the regions with galactic latitudes less than about 20°. The situation with rocket, Apollo and space shuttle measurements is different: while the embarked instruments were specifically designed for background observations, the limited observing time did not allow a scan of large solid angles of the sky.

The only existing whole-sky survey of UV light made with sufficient sensitivity was made with the ELZ package on board the D2B-AURA satellite (Maucherat-Joubert, Deharveng, and Cruvellier, 1980; Joubert et al., 1983).

There have been, and are still strong discrepancies between the results of all these measurements. However most agree in finding correlations between the UV diffuse galactic light and the column density of atomic hydrogen although the slopes of the corresponding regression lines vary from observation to observation. Amongst published papers, the one by Jacobsen, de Vries, and Paresce (1987) contains a comparison between the intensity I(UV) of the far-UV diffuse light, N(H) and the 100 μm intensity I(100) from IRAS. While there is a rather tight correlation between I(100) and N(H), the correlation between I(UV) and any of these quantities is loose although real. In the next section, I will re-examine this problem on the basis of a new analysis of the D2B satellite results.

3. THE FAR-UV BACKGROUND FROM A NEW ANALYSIS OF THE D2B SATELLITE WHOLE-SKY SURVEY

The ELZ spectrophotometer on board the D2B-AURA satellite launched in 1975 has been described by Maucherat-Joubert et al. (1979). The instrument scanned the sky along ecliptic meridians at 90° elongation, with a rotation period of 4.6 minutes. The whole sky has been scanned with the exception of a small strip, with an effective field of view of 1 × 2.7°. Observations were performed in four UV spectral bands. Only those in two bands (1690 Å and 2200 Å) are useful for diffuse light studies. After the contributions of the dark current and of the zodiacal light have been subtracted, histograms of the count rates for all the data points falling in a given area of the sky are constructed. If the area is uniformly emitting, these histograms should obey the Poisson distribution. However, the individual stars add a high-count skewness and tail to this distribution, which varies in importance from place to place. At galactic latitudes larger than about 30° the stars brighter than m(UV)=8 roughly are found only in the tail, but of course unresolved grouped fainter stars may also contribute to the tail. In the initial analysis of the data (Joubert et al., 1983) the identified stars seen at the 2.5 sigma level on individual scans were removed, and the areas showing a residual tail were further eliminated. Moreover, only latitudes larger than 30° were analysed in areas of about 30 deg^2.

We realized later that this analysis was too restrictive, and a new one has just been performed on the data at 1690 Å by M. Hanus, M. Pérault and me. We worked on smaller areas of about 16 deg^2 without initial elimination of the identified stars and rejected only those regions for which it was hopeless to see the background Poisson distribution amidst the stellar contribution. The result is the preliminary map with about 5 × 5° resolution displayed on Figure 1a. We believe this map to be essentially free of direct stellar radiation (at galactic latitudes larger than 30°). As discussed by Joubert et al. (1983) the residual contribution of unresolved stars should be generally smaller than 50 units at those latitudes (1 unit = 1 photon cm^{-2} s^{-1} Å^{-1} sr^{-1}), unless there is an important contribution of many faint evolved stars. This possible contribution is likely to be smooth and will not affect local deviations to the correlations; moreover I will show later that it is not likely to be dominant. At lower galactic

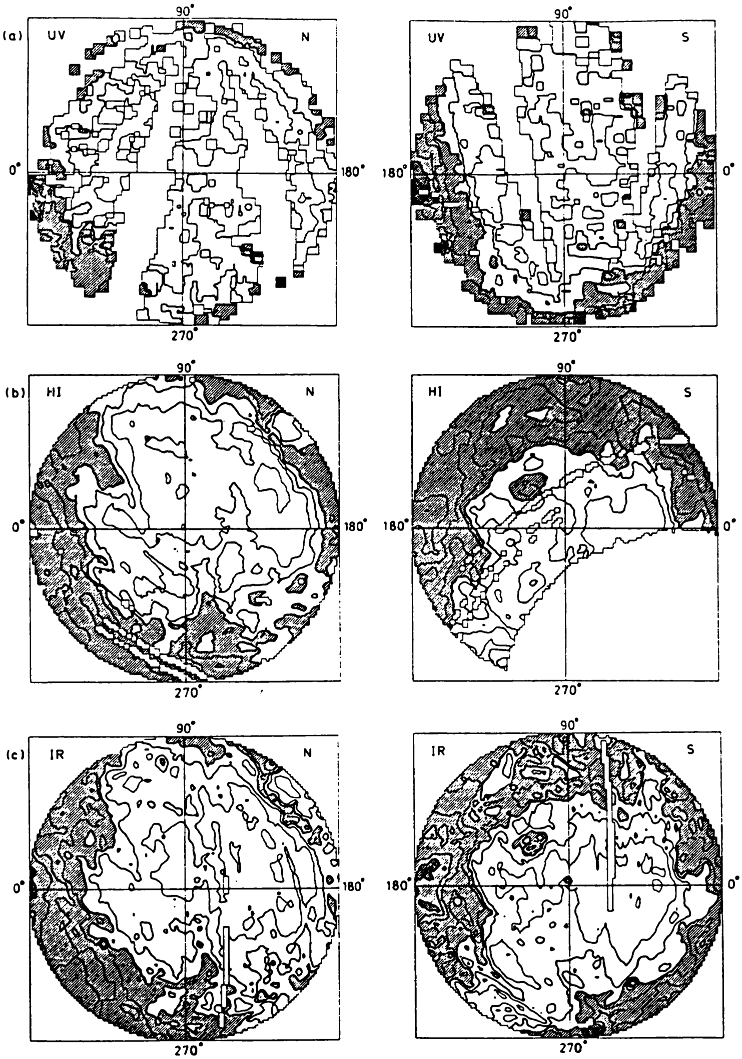

Figure 1. Galactic polar-cap maps of the far-UV background radiation at 1690 Å, of the 21-cm radiation (from Stark et al., 1989) and of the 100 μm radiation (from Boulanger and Pérault, 1988). The latitude range is from 30 to 90° (N maps) and from –30 to –90° (S maps), with a linear scale. The angular resolution of the UV maps (Figure 1a) is about 5 × 5°, and the contours are 900, 1200, 1500, 1800, 2100, 2400, 2700 and 3000 photons (cm^{-2} s^{-1} $Å^{-1}$ sr^{-1}). The areas without contours delineated by thin lines contain no usable data. The angular resolution of the HI maps (Figure 1b) is 2 × 2°, and the contours are 50, 100, 150, 200, 270, 400, 650 and 1000 K(km/s); to convert to column densities of HI in atoms/cm^2, multiply by 1.823 E18. The angular resolution of the 100 μm maps (Figure 1c) is 1.5 × 1.5°, and the contours are 1.6, 2.4, 3.2, 4, 5, 7, 10 and 15 MJy/sr. The far-UV map should be considered as provisional.

latitudes there is probably an important contribution from direct starlight and this portion of the map is not displayed.

Figures 1b and 1c display for comparison with Figure 1a maps of the 21-cm emission from the Bell Laboratories survey and of the 100 µm galactic emission from IRAS. The following discussion is based on the comparison of these maps with the far-UV one.

4. COMPARISON OF FAR-UV, HI, AND FAR-IR MAPS

The correlation between the UV intensity at 1690 Å and N(H) for galactic latitudes larger than 30° has already been discussed by Joubert et al. (1983), giving

$$I(1690) = (9.56 \pm 0.46) 10^{-19} N(H) + \text{constant},$$

I(1690) being in photon units and N(H) in atoms cm^2. The meaning of the intercept is discussed in this paper. The correlation between the newly reduced data UV and the Bell Laboratories HI data is essentially the same. As the far-IR/HI correlation is quite tight (see Boulanger and Pérault, 1988, Figure 5) the UV/far-IR correlation is similar to the UV/HI one. Do these correlations imply that most of the far-UV radiation at high galactic latitudes is starlight scattered by dust? Clearly such relations are dominated by the cosec(b) variation with galactic latitude b which is expected for any quantity with a plane-parallel galactic distribution. For example, if the far-UV radiation were due to the contribution of faint unresolved stars, it would exhibit a cosec(b) dependence as HI and the far-IR radiation do and a correlation would naturally appear between these quantities. It is necessary to consider the differences between the observed values and the average emission at their galactic latitudes as given by a mean cosecant law drawn through the data. The correlation between these differences, if any, implies a real physical correlation between the quantities under consideration.

The relation between the differences between data points and a fitted average cosecant law is presented by Boulanger and Pérault (1988, Figure 3) for HI and the far-IR. Figure 2a is a plot of those differences for the far-UV data vs. HI, and on Figure 2b the same for the far-UV vs. the far-IR data. A positive correlation appears in both cases, although with a large scatter. The slopes are fully consistent with those determined directly from the data without subtraction of a cosecant variation: this shows that most of the far-UV radiation is indeed linked with gas and dust and is thus scattered starlight.

In their analysis, Joubert et al. (1983) had noticed a skewness in their far-UV/HI correlation with conspicuous excesses in UV fluxes. The excesses at 2200 Å and at 1690 Å occur in the same areas of the sky. They seemed to correspond to inner regions of large HI shells and were attributed either to 2-photon emission following recombination of ionized hydrogen in those shells or to stellar radiation scattered by dust not associated with atomic hydrogen. Line emission or molecular hydrogen fluorescence are eliminated by the simultaneous occurrence of the excesses at 2200 Å and 1690 Å.

Similar excesses appear in the correlations of Figure 2 and in a direct comparison of Figure 1a with Figures 1b and 1c, confirming the previous results. As they generally appear with respect to both HI and the far-IR intensities, they cannot be due in general to scattering by large grains (those radiating at 100 µm). Scattering by smaller grains is not excluded, but the favored explanation is 2-photon emission. The most convincing case for this mechanism is the UV-excess region centered on Spica (alpha Vir) at $l = 316°$, $b = +51°$, well visible on the lower-left part of Figure 1a North. This excess cannot be fully due to UV light from this star scattered in the instrument, as the second brightest far-UV star at high galactic latitudes, alpha Eri with 0.8 times the flux of Spica at 1690 Å, does not appear on the map at $l = 291°$, $b = -59°$. Reynolds (1985) has found an extended faint HII region around Spica with a peak intensity of 5 Ry. This nebula coincides in extent and position with the UV-excess region, and its intensity is slightly larger than the predicted intensity assuming the relation between the

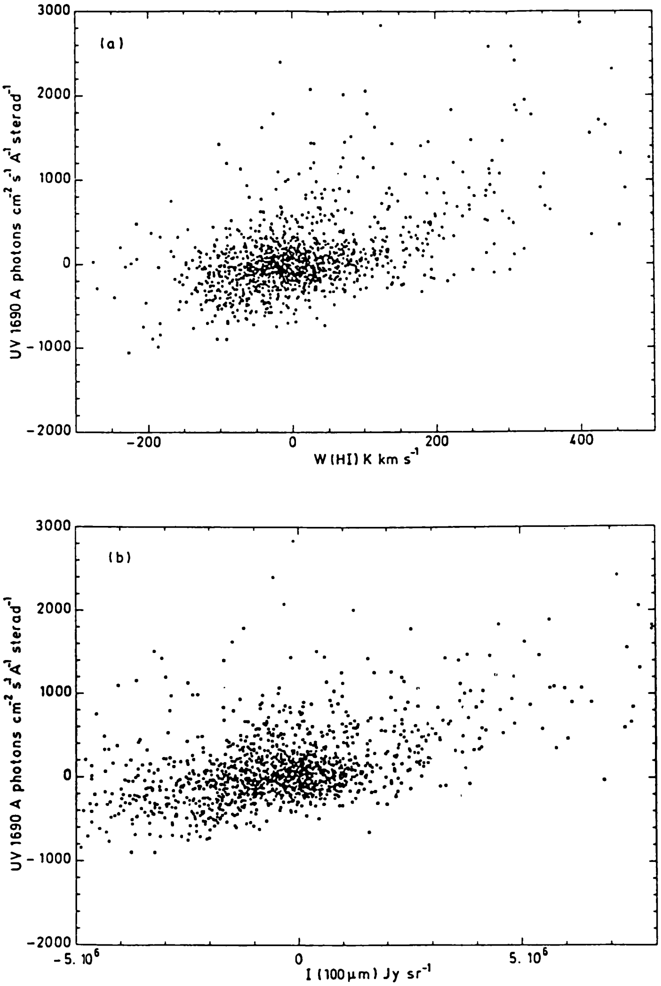

Figure 2. Plots of the differences between data points and mean cosec(b) laws (see text), for galactic latitudes larger than 22°. a) far-UV residuals vs. HI residuals, over pixels 4 × 4° in size. b) far-UV residuals vs. 100 µm residuals, over pixels 4 × 4° in size.

2-photon intensity near 1690 Å and the H alpha intensity of 60 photon units/Ry given in the review by Reynolds in this volume.

Other more or less extended excesses are visible on Figure 1. At *l* = 134°, *b* = 32°, there is a HI and far-IR hole corresponding to the interior of a shell discussed by Reach, Heiles, and Koo, (1989, this volume), but there is no UV hole at this position. There are other more extended UV excesses in the Eridanus-Orion loop region (already discussed by Joubert et al., 1983). The HI and far-IR hole at *l* = 212°, *b* = –43° does not appear on the UV map. A strong localized excess is visible at *l* = 230°, *b* = 48° without obvious HI and far-IR associated features, etc. It will be very interesting to attempt detection of H alpha in these regions.

5. SOME REMARKS ON THE INTERPRETATION OF THE UV/HI/IR CORRELATIONS

It is clear that the interpretation of similar UV-HI correlations may give different results as to the properties of the scattering grains, depending on the model used for the distribution of the illuminating stars and of the scattering material in our Galaxy. For example, a very similar UV/HI correlation is observed at almost the same wavelength by the D2B satellite and in the UVX shuttle observations (Hurwitz, Bowyer, and Martin, 1989, this volume). Joubert et al. (1983) interpreted the D2B observations using the simple model of Jura: assuming an albedo a=0.5 they find a scattering asymmetry factor g=0.8, while using another model Hurwitz et al. find a=0.2 and a very small g. None of these (a,g) sets match the results of Witt (1989, this volume) obtained from studies of the low-latitude UV light and of reflection nebulae: a=0.1–0.5, g=0.6 (uncertain). Clearly more realistic models of star and dust distribution are needed. But I want also to draw attention to other factors which may introduce further difficulties.

First, there might be systematic variations in the properties of dust with distance to the galactic plane. Boulanger and Pérault (1988, Table 4) have shown that the 60µm/100µm intensity ratio is larger at high galactic latitudes. Kiszkurno-Koziej and Lequeux (1987) have shown that the far-UV rise in the interstellar extinction curve is stronger at larger distances from the plane. There might be a physical link between these two effects.

Second, the clumpiness of the interstellar clouds is likely to play a role in their scattering properties. Early studies of this problem in the large-scale galactic context are due to Mattila (1971) and to Caplan and Grec (1979). The internal clumpiness of the dense interstellar clouds is well known, but even the relatively transparent, high-latitude clouds are clumpy. This clumpiness is apparent on the IRAS cirrus maps and exists down to scales of 20″(0.01 pc at a typical distance of 100 pc; Guhathakurta and Tyson, 1989, this volume). Model calculations of radiation transfer in partly scattering, partly absorbing clumpy interstellar clouds have recently been made by Boissé (1989) using both analytical and Monte-Carlo methods. The general result is that for a constant mean density in a cloud, its degree of transmission increases greatly with increasing clump-interclump contrast while its reflectivity is decreased to a lesser degree and its absorptivity is essentially unaffected. As a result, systematic effects are likely to arise in the comparison of albedo and phase function asymmetry between relatively opaque regions like reflection nebulae where the effect of clumpiness is major, and high-latitude, more transparent clouds where these effects are not important. Even at high galactic latitudes, variations in the degree of clumpiness may introduce a scatter in the extinction/N(H) relation which contributes to the scatter in the comparison between extinction (from galaxy counts) and N(H) discussed in Section 2.2. Clumpiness will not play a role in the far-IR/N(H) relation for high galactic latitudes, whose scatter must be due to another cause, most probably to real variations in the dust properties. Finally, clumpiness may participate together with variations in the dust properties, 2-photon emission and to some extent H2 fluorescence (Martin, Hurwitz, and Bowyer, 1989, this volume), to the large dispersion in the UV/HI and UV/far-IR correlations.

Acknowledgments — I thank M. Hanus and M. Pérault for their efficient help in reducing the data used for this paper and in preparing the figures, and J.-L. Puget and R. Reynolds for discussions.

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K. Mattila: *When calculating the expected amount of scattered light, the model with a light source in the plane (Jura) appears very crude and too unrealistic.*

J. Lequeux: I fully agree. Now that good quality data are becoming available, it is imperative to use a more refined model taking into account the actual spatial distribution of the illuminating stars and — as well as possible — the distribution of the scattering matter.

R. Kimble: *How does the slope of your UV/HI correlation compare with the recent Berkeley UVX result?*

J. Lequeux: The UV/HI correlation obtained from the D2B data is essentially the same as that obtained at relatively faint column densities in the recent Berkeley UVX observation (Hurwitz et al., this volume).

G. Verschuur: *Concerning the clumpiness of the interstellar medium, an analysis of published data concerning diameters of HI clouds shows that they are usually about three times the telescope beam diameter. This implies large-scale existence of unresolved structure. This has important implications concerning your advice to use Bell Labs's 21 cm data for comparing with IR data. The Bell Labs data may give you more accurate N_H values but will do little to reveal the physical nature of the HI structures that are lost in their beamwidth.*