THE HIGH-LATITUDE SKY AT IR, OPTICAL, AND UV WAVELENGTHS

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ABSTRACT. We review the current data on the not-so-dark sky covering infrared, visible and ultraviolet wavelengths. Here, we are mainly concerned with the emission from the interstellar gas and dust above and below the galactic plane. Zodiacal light is not discussed in detail and emission from unresolved stars is briefly mentioned. Recent improvements in these studies have been made with the use of new satellite UV data, the use of high-performance CCD in the visible spectrum and extensive analyses from the *Infrared Astronomical Satellite* (IRAS). We show that cirrus clouds which subtend a large solid angle at high galactic latitudes are made of neutral gas and dust, are within a few hundred parsecs of the Sun, and are almost optically thin up to UV wavelengths. The brightness of these clouds, expressed as $\nu I_\nu = \lambda I_\lambda$, is estimated to be within 10^{-8} and $10^{-7}\,\mathrm{W\,m^{-2}\,sr^{-1}}$ at almost all wavelengths from $\lambda = 0.1$ to $300\,\mu$m and peaks at $150\,\mu$m, for a typical column density of $3 \times 10^{20}\,\mathrm{H\,cm^{-2}}$. They may yield the fundamental limitation to all extragalactic and halo studies.

1. INTRODUCTION

The high-galactic latitude sky has long been the domain for extragalactic studies. However, due to improvements in the sensitivity of the astronomical instruments, it has become possible to investigate the nature of the thin layer of galactic matter that separates us from intergalactic space (see this entire conference). Due to the proximity of the high latitude matter, one can observe phenomena with a better spatial resolution and less confusion problems than those usually occuring in studies of the galactic plane. Therefore, by generalisation, one can hope to gain a better physical picture of the whole galactic matter. In the following, we will review the present knowledge of the high latitude matter that has been gained so far and we will be mainly concerned with high-latitude interstellar (IS) matter: gas and dust, as revealed by its diffuse emission from IR to UV wavelengths. Sky specific brightnesses will be expressed as $\nu I_\nu = \lambda I_\lambda$ (*i.e.* per unit log of frequency or wavelength) in units of $1\,\mathrm{nW\,m^{-2}\,sr^{-1}} = 10^{-9}\,\mathrm{W\,m^{-2}\,sr^{-1}}$. In case of an unresolved

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line, we will indicate some adopted filter band $\Delta\nu$ and an equivalent brightness for the integrated line: νI_ν such that $(\nu I_\nu)\Delta(\log \nu) = \int d\nu I_\nu$.

2. THE EMISSION OF HIGH-LATITUDE GAS

The 21 cm emission from the galactic HI gas has been thoroughly discussed in this conference (see the articles in these proceedings by Burton, Lockman, Mirabel, Verschuur, and Wakker) as well as the 3 mm emission from the CO-molecular gas (Blitz), the UV emission lines from highly ionized gas (Savage), and the $0.6563\,\mu\mathrm{m} = H_\alpha$ emission from the H^+ gas (Reynolds). Here, for completeness, we would like to point out other emission processes from the gas ocurring at UV and IR wavelengths, mainly the H_2 fluorescence and the gas cooling via far infrared lines; 2-photon processes are unimportant: Deharveng, Joubert and Barge 1982.

2.1 H_2 *emission*

H_2 molecules cannot be directly photodissociated by the UV photons of the interstellar radiation field (ISRF). From the absorption of a UV photon (of wavelength $\lambda \geq 0.11\,\mu\mathrm{m}$) the hydrogen molecule is excited to the Werner or Lyman energy levels (Duley and Williams 1980). The molecule returns to the ground electronic level on a vibrationnally excited level $v \geq 0$ by the emission of a UV photon. It is only when $v \geq 15$ that the molecule is dissociated. On average 9 photons will be emitted before the H_2 dissociation occurs. The deexcitation UV photons have specific wavelengths within the Werner (around $0.10\,\mu$m) or Lyman (around $0.16\,\mu$m) bands. The emission of these photons from molecular hydrogen in the diffuse IS medium (Jura 1974) was predicted by Duley and Williams (1980). Suspected by Jakobsen (1982), the Lyman band photons have just been clearly detected at high latitude for the first time by Martin, Hurwitz and Bowyer (1990, hereafter MHB). The presence of molecular hydrogen is proved in direction where CO has previously been detected. Moreover, "halos" of H_2 fluorescence are shown to exist even where CO is not detectable. Other regions do not show any detectable H_2 emission. MHB suggest that the molecular halos are the result of photodissociation of dense molecular clumps. From the observed intensity of the Lyman band I_0 one can infer the speed at which H_2 is dissociated:

$$v_d = 8 \times 10^{-3}\,\mathrm{pc/Myr}\,(n_{H2}/50\,\mathrm{cm}^{-3})\,(I_0/3 \times 10^4\,\mathrm{phot.\,cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1})$$

which implies a relatively slow process: a $10 M_\odot$ cloud of H_2 density $50\,\mathrm{cm}^{-3}$ will be destroyed in typically 100 Myr. The same Werner and Lyman photons have recently been observed in one reflection nebula by Witt *et al.* (1989) who concluded that it was UV pumping rather than shocks that can produce this fluorescence. Finally, let us remark that in reflection nebulae, an *infrared* $\simeq 2\,\mu$m rotation-vibration spectrum of lines from molecular hydrogen has been observed (Gatley *et al.* 1987, Sellgren 1986) that correspond to the end of the cascade to the ground state (Sternberg 1989, Sternberg and Dalgarno 1989). Hence one could try to observe this infrared counterpart of molecular fluorescence in the IS medium. However, from the clouds observed by MHB one can deduce an equivalent brightness of about $0.6\,\mathrm{nW\,m^{-2}\,sr^{-1}}$ in lines covering 1 to $3\,\mu$m which is quite weak.

2.2 Gas cooling emission

The neutral IS medium cools mainly via two fine-structure lines of oxygen and ionized carbon atoms at $63\,\mu$m and $158\,\mu$m with about the same brightness. It is far from certain that the oxygen line significantly contributes to the $60\,\mu$m IRAS emission from the diffuse high-latitude medium (cirrus clouds) (see the propositions by Harwitt *et al.* 1986 and Stark 1990 and counter-arguments by Terebey and Fich 1986 and Verstraete 1990). This is a hot topic that should receive a clear answer within the next few years with the Kuiper Airborne Observatory, the *Infrared Space Observatory* (ISO) and maybe earlier with the now in orbit *Cosmic Background Explorer* (COBE). The FIRAS instrument on COBE covers a range of wavelengths from $100\,\mu$m to 1 cm with a spectral resolution of few percent and a beam of 7 deg. and has a sensitivity in νI_ν of about $1\,\mathrm{nW\,m^{-2}\,sr^{-1}}$. Table 1 and Figure 1 give some estimated values for the gas emission.

3. THE DUST-LIGHT INTERACTION AT HIGH LATITUDES

The IS dust acts as a veil for the light emitted by stars. Studies of the way dust interacts with light allow us to deduce the properties of the incident stellar radiation field but also of the intervening matter. We can assume that the high-latitude dust is almost optically thin up to UV wavelengths since a typical cloud column density of $N_H = 3 \times 10^{20}\,\mathrm{H\,cm^{-2}}$, which we will use as an example in the following, corresponds to a visible extinction $A_V \simeq 0.16$ mag and an extinction of about 0.70 mag at $0.1\,\mu$m (Savage and Mathis 1979). While in the seventies it was thought that dust could be observed only in the visible (scattering) and far infrared (FIR thermal emission) we would like to show that new observations lead us to a picture where the light reprocessed by dust occurs at almost all wavelengths from submillimeter to UV wavelengths. Table 1 and Figure 1 illustrate this point of view and are extensively discussed in the following for what concern: 1) the UV and visible scattering, 2) the optical luminescence, and 3) the IR emission.

3.1 UV and visible dust scattering in a high-latitude cloud

We consider first an example of UV observations taken by the *D2B* satellite (Joubert *et al.* 1983) and reanalysed by Pérault, Lequeux, Hanus and Joubert (PLHJ 1990). PLHJ have attempted to remove some striping that was present in the broad band data at $0.169\,\mu$m by using the North Ecliptic Pole as a reference and correcting for gain variations with time. The effective beam is about $2° \times 2°$. One can compute the average at constant latitude ($|b| \geq 30°$) of the UV sky brightness as a function of $1/sin(b)$. This can then be compared with the same average (done

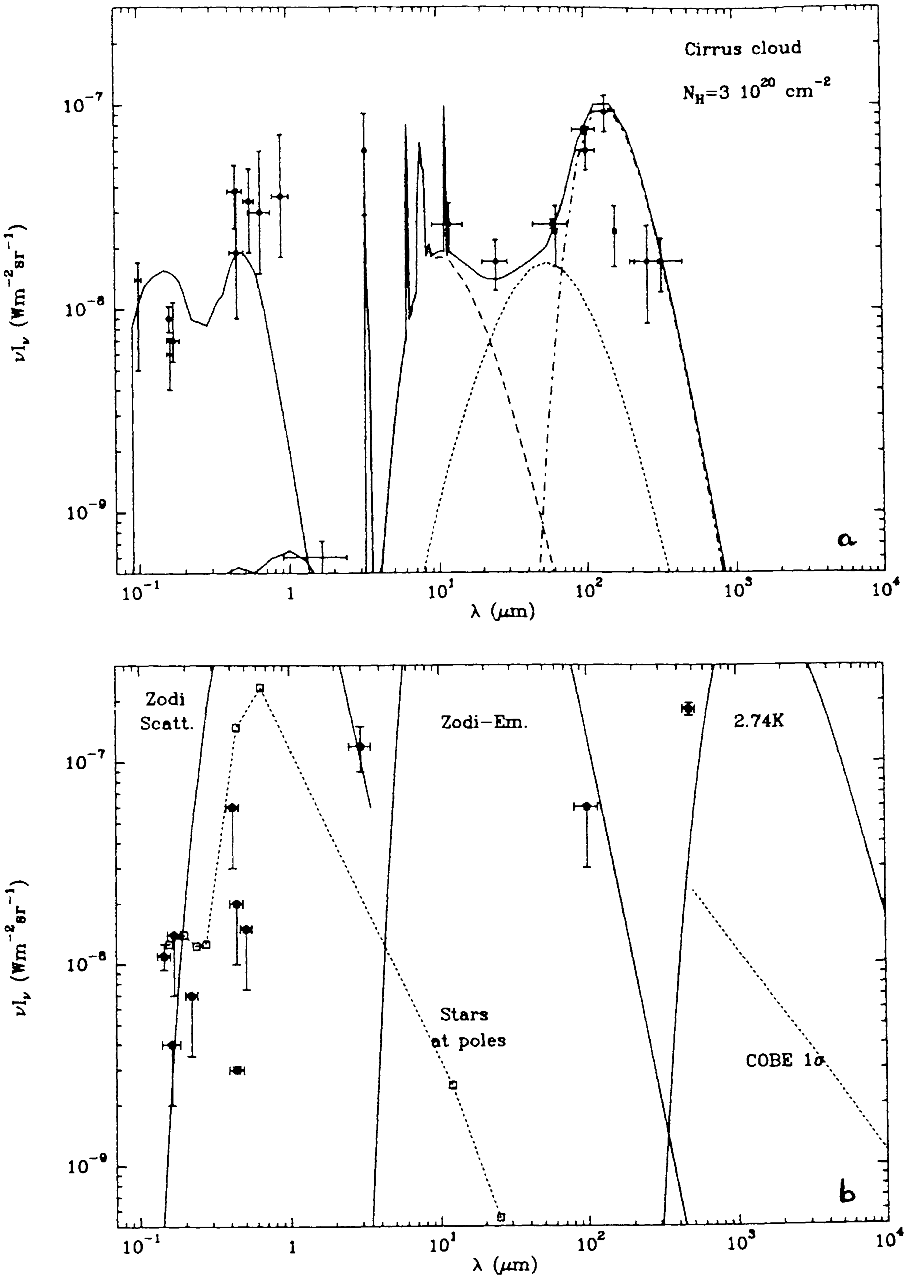

Figure 1. (a) Brightness of a neutral IS cloud (see Table 1). Continuous line is from a three component dust model (PAHs: long-dashed, very small grains: short-dashed, big grains: alternate-dashed) by Désert, Boulanger and Puget (1990). The visible and UV part is normalised with GT observation at B_J band. Observations of gas emission are noted with error bars without a central dot whereas dust emission observations have a central dot. (b) Backgrounds and foregrounds at the galactic poles in the same units and scales (see Section 4)

on exactly the same areas in the sky) of the 100 μm *IRAS* map made by Boulanger and Pérault (hereafter BP 1988). They both roughly follow a cosecant law that is typical of material distributed in a plane-parallel geometry. Whereas it is known (see BP and Section 3.3) that the FIR emission is associated to dust in the HI neutral medium, it is not enough that the UV brightness follows a cosecant law to be certain that the UV comes from dust scattering of the ISRF. Integrated light from faint UV stars could produce this effect as well. Therefore it is instructive to subtract the average cosecant law from both UV and IR data in order to see if "clumps" of emission correlate or not. The result is shown in Figure 2 (here for the North galactic pole). The map of the excesses are shown in Figure 3. PLHJ conclude that UV scattering by dust of the ISRF is at the origin of the UV brightness of the sky because Figure 2 shows a positive correlation and the deduced ratio of UV to IR brightness is the same as the ratio of the cosecant laws. Note that some UV excesses in Figure 2 and 3 are probably due to scattering in the telescope of the UV light from single stars and may not be real.

Other studies of the UV sky brightness by Jakobsen *et al.* (1984 and 1987), Morgan *et al.* (1978), Hurwitz *et al.* (1989) and Fix *et al.* (1989) have also revealed a correlation with HI gas. However, Murthy *et al.* (1989 and 1990) do not find such a correlation and the slope of the previously mentioned correlations do not agree with each other: *e.g.* PLHJ find a brightness at 0.169 μm of about $\nu I_\nu \simeq 7\,\mathrm{nW\,m^{-2}\,sr^{-1}}$ for $N_H = 3 \times 10^{20}\,\mathrm{H\,cm^{-2}}$ whereas Jakobsen *et al.* (1987) find at 0.214 μm a brightness of $36\,\mathrm{nW\,m^{-2}\,sr^{-1}}$. The standard interpretation for a correlation between the UV brightness of the sky and its FIR (or HI emission which is closely related, see BP) is that the IS dust produces both. The UV part is scattering of the ISRF and FIR is thermal dust emission (Jura 1979). For low optical depth, the UV brightness is proportional to the ISRF and the scattering optical depth, for a given dust asymmetry factor and a given latitude, whereas the FIR emission is proportional to the ISRF and the absorption optical depth. The correlation indicates a rather constant albedo which is the ratio of the scattering optical depth to the extinction (scattering plus absorption) optical depth.

Dust scattering at optical wavelegenths and at high latitudes has been discovered earlier and is more firmly established. de Vaucouleurs (1960) already mentioned some faint optical filamentary nebulosity in the vicinity of (but not associated with) the Large Magellanic Cloud. Sandage (1976) has shown the pervasiveness of these faint reflection nebulosities at high latitudes, later to be dubbed "cirrus" clouds with IRAS (Low *et al.* 1984). de Vries and Le Poole (1985) have clearly demonstrated from photographic plate analyses the correlations between the visible diffuse brightness of the sky, the visible extinction and the FIR emission.

3.2 Optical luminescence

Recently, Guhathakurta and Tyson (GT 1989) used a mosaic of CCD frames at B_J, R and I bands to observe these high-latitude nebulosities. Beside the general association of optical emission with FIR emission, GT find that there is a red excess of emission compared with the dust scattering expectations. This excess is

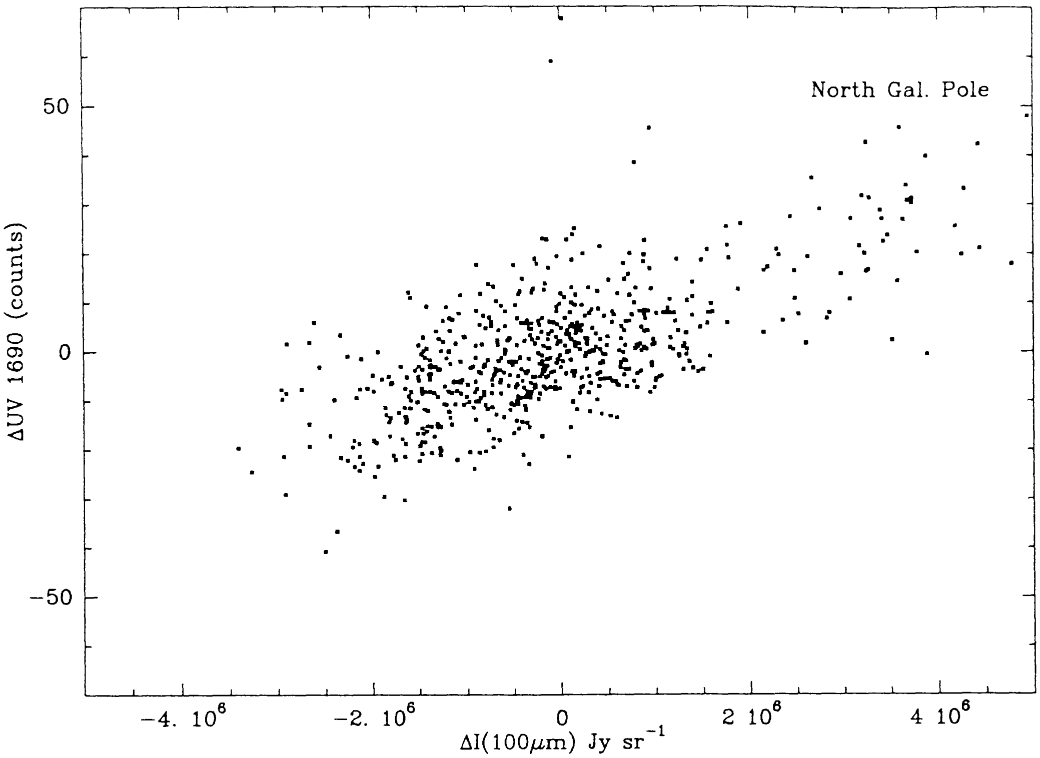

Figure 2. Correlation between UV and IR excesses over the cosecant law for the North Galactic polar cap ($b \geq 30°$) where each pixel (25 sq.deg. large) is shown as a dot. One UV count is $0.4\,\mathrm{nW\,m^{-2}\,sr^{-1}}$ in a bandwidth of $0.033\,\mu\mathrm{m}$.

identified with the red excess from 0.550 to $0.850\,\mu$m that is observed in reflection nebulae (*e.g.* Witt and Schild 1985) and even high latitude dark nebulae (Mattila 1979) and has a complex, varying, and as yet unidentified spectral structure (Schmidt, Cohen and Margon 1980, Witt and Boroson 1990). Candidates for this broad red excess all imply some form of carbon dust grains: diamond-like (Duley and Williams 1988), hydrogenated amorphous carbon grains (Witt and Schild 1988) or Polycyclic Aromatic Hydrocarbon (PAHs) molecules (d'Hendecourt *et al.* 1986). The involved emission mechanism is usually thought to be luminescence *i.e.* a cascade in low electronic levels of UV-excited very small grains.

3.3 Infrared emission

A review of the high-latitude IR sky has already been given by Boulanger (1989). Here, we merely want to stress the main points. The diffuse IR sky, as IRAS showed us wonderfully, is dominated by IS dust emission, once the zodiacal light is removed. BP have used a similar technique as that used in Section 3.1 to show that IR emission is closely associated with the HI neutral medium. The infrared sky has also revealed that a non-negligible fraction ($\sim 30\%$) of IS dust emission occurs at shorter wavelengths ($\lambda \leq 80\,\mu$m) than grains can emit if they are at an equilibrium temperature. The current interpretation is that very small grains and/or large

TABLE 1.
Scattering and emission from a 3×10^{20} H cm^{-2} cirrus cloud

λ μm	νI_ν nW m^{-2} sr^{-1}	HWHM μm	σ_+ nW m^{-2} sr^{-1}	σ_- nW m^{-2} sr^{-1}	Comments, ref.
			Gas emissivity		
0.100	14.	0.005	3.	9.	Werner H_2 (1)
0.160	6.	0.008	1.2	2.	Lyman H_2 (2)
1.65	0.6	0.75	0.12	0.12	H_2 rot.-vib. (3)
63.	24.	1.6	8.	8.	Oxygen line (4)
158.	24.	3.95	8.	8.	C^+ line (4)
			UV-visible dust emissivity		
0.158	9.	0.0015	1.3	1.3	UVX (5)
0.169	7.	0.0165	3.8	1.5	D2B (6)
0.441	38.	0.049	13.	13.	Pioneer 10 (7)
0.450	19.	0.049	20.	10.	CCD (8)
0.550	34.	0.045	15.	15.	Photo. plate (9)
0.650	30.	0.110	30.	15.	CCD (8)
0.900	36.	0.120	36.	18.	CCD (8)
			IR dust emissivity		
3.3	60.	0.025	31.	31.	Balloon (10)
12.	26.	2.85	7.1	7.1	IRAS (11)
25.	17.	4.9	4.8	4.8	IRAS (11)
60.	26.	15.5	1.4	1.4	IRAS (11)
100.	76.	17.8	2.9	2.9	IRAS (11)
102.	60.	15.3	12.	12.	Rocket (12)
137.	93.	24.	19.	19.	Rocket (12)
262.	17.	47.	8.6	8.6	Rocket (12)
325.	17.	125.	5.	5.	Balloon (13)

Notes to Table 1: The νI_ν brightness unit is nW m^{-2} sr^{-1} $= 10^{-9}$ W m^{-2} sr^{-1}. The brightness uncertainties σ_+ and σ_- have been estimated from the quoted references and include true variability. HWHM is the spectral coverage half-width at half maximum that is assumed for the brightness calculation (see Section 1 for definition).

References: (1) when detected, deduced from Lyman band (not yet observed); (2) when detected (MHB); (3) estimated using Sternberg 1989 (not yet observed); (4) estimated using a 5% spectral resolution and a ratio of the efficiency of heating the gas by small grains to IR emission of 6% (Verstraete 1990) (not yet observed); (5) Martin *et al.* 1989; (6) PLHJ see text; (7) Toller 1981; (8) GT 1989; (9) Sandage 1976; (10) Giard *et al.* 1989; (11) cosecant law from BP; (12) Lange *et al.* 1989; (13) Fabbri *et al.* 1986.

molecules have temperature fluctuations due to their low heat capacity and to the individual photon heating events (see Puget and Léger 1989 and references therein). About 10 to 20% in mass of IS dust is necessary to explain the short wavelength emission (Désert, Boulanger and Puget 1990). In addition, evidence for the existence of large molecules *e.g.* PAHs is given from observations of the so-called unidentified emission features (3.3, 6.2, 7.7, 8.6 and 11.3 μm) in reflection nebulae (Sellgren 1984) and the diffuse medium (Giard *et al.* 1989).

Questions that are still open concerning the IS dust IR emission are related to the dust content of the other phases of the IS medium. Is the warm ionised medium dust-deficient or spatially correlated with the HI medium as suggested by BP (see also Abraham 1990)? Is the large 60/100 μm ratio (0.3 to be compared with 0.2 on average outside the galactic disk) observed in the polar caps indicating some dust processing in the nearby IS medium? What is the distance to the cirrus clouds (see *e.g.* Magnani and de Vries 1986, Franco 1989, typical distances are in the 50 to 200 pc range)? What is the velocity structure of cirrus clouds (*e.g.* Deul and Burton 1990) and are the IR colors (hence dust composition and heating) varying (*e.g.* BP, Terebey and Fich 1986, Herter, Shupe and Chernoff 1990)?

4. FOREGROUNDS AND BACKGROUNDS

The picture that was drawn in the preceding sections would be misleading if we did not mention the presence of strong foregrounds and backgrounds which have to be understood in order to be subtracted. Figure 1b, which was purposely drawn on the same scale as Figure 1a, shows the various fore-backgrounds which are in general *one to two* orders of magnitude above the cirrus cloud brightness. The zodiacal scattering at the galactic poles is estimated by assuming constant reflectivity of interplanetary dust (continuous curve on the left). The unresolved stars (dashed curve and open squares) also produce a background at the same UV to IR wavelengths that has been observed by Gondhalekar *et al.* (1980) in the UV, Toller *et al.* (1987) in the visible and estimated by BP in the IR. The Zodiacal emission (second continuous curve) is the strongest foreground in the IR. It follows approximately a blackbody curve modified by an emissivity $\propto \lambda^{-1}$ (Hauser *et al.* 1984). The cosmic microwave background (continuous curve on the right) follows a perfect blackbody law with $T = 2.735\,\mathrm{K}$ as demonstrated by the COBE satellite (Mather *et al.* 1990).

Looking at Figure 1b, one can see that there are three main extragalactic spectral windows ($\lambda \leq 0.15\,\mu$m, $\lambda \sim 3$, and $\sim 300\,\mu$m) where the various fore-backgrounds are relatively weak. It should be no surprise that there have been several claims (but as yet unconfirmed) of an extragalactic background in all these windows (points on Figure 1b with symmetric error bars) *e.g.* by Fix *et al.* (UV, 1989), Tyson (visible, 1988), Matsumoto *et al.* (near-IR, 1988a), Rowan-Robinson (far IR, 1986 treated as an upper limit by BP) and Matsumoto *et al.* (submillimetre, 1988b). Other observations have yielded upper limits to an extragalactic background (error bars pointing downwards) from UV to IR: Martin, Hurwitz and Bowyer (1989),

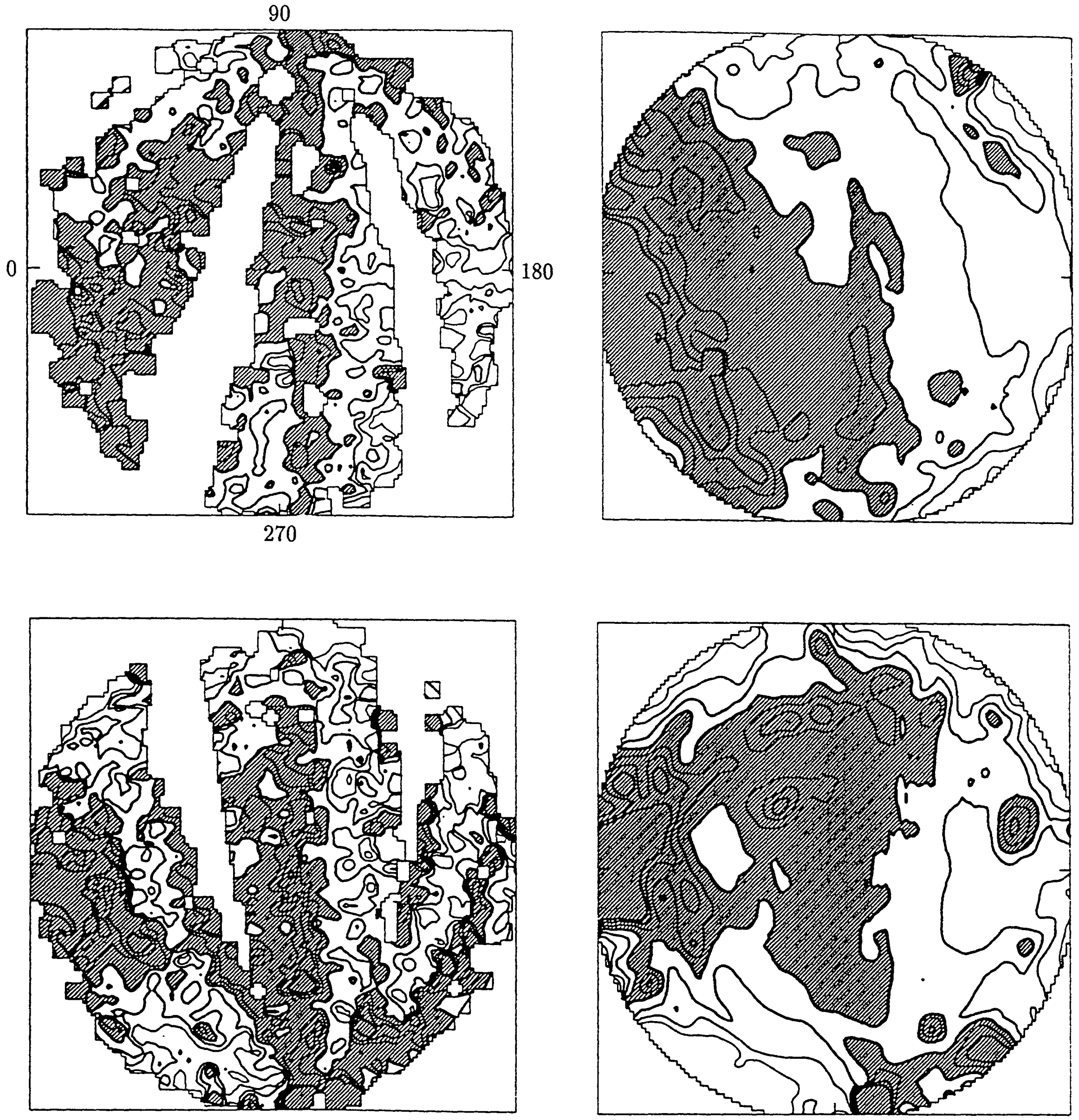

Figure 3. Contour and greyscale plot of the polar caps: top is North, bottom is South. Galactic poles are at the center of the maps, and radii are proportional to galactic latitudes from 90 to 30° or −90 to −30. Polar angle is galactic longitude. On the left is the UV brightness and on the right is the far IR (100 μm) brightness. Both are cosecant law subtracted. Therefore the small-scale features are enhanced. The thickest contour (thickness 4) is the zero level. Contour thickness goes as the sequence 1 2 3 4 1 2 3. The increment for the contours is $3\,\mathrm{nW\,m^{-2}\,sr^{-1}}$ in a 0.033 μm band and 1 MJy/sr resp. Grey parts correspond to positive excesses over the cosecant law, and white parts to negative excesses.

Joubert *et al.* (1983), Spinrad and Stone (1978), Toller (1983), Dube, Wickes, and Wilkinson (1977), Mather *et al.* (1990 right dashed curve).

Spatially, one wants to find the extragalactic windows where local emission is the least bright. Let us mention the areas given by BP and by Jahoda, Lockman, and McCammon (1990). The latter authors find that any line of sight (with a beam of 21′) contains at least $\sim 0.5 \times 10^{20}\,\mathrm{H\,cm^{-2}}$. Therefore a scaling of Figure 1a downwards by a factor ~ 6 gives the minimum cirrus brightness anywhere in the sky and gives the fundamental limit for the study of diffuse extragalactic backgrounds. These windows may prove useful for the study of the galactic halo emissions as well.

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