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ASTRONOMY
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Models for Interpreting the Diffuse Galactic Light

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Summary. The stars which act as primary light sources have a wider distribution perpendicularly to the galactic plane than the dust which causes the diffuse galactic light. This situation is approximated by a model in which a fraction F of the starlight is distributed in proportion to the dust and a fraction $1-F$ illuminates the dust layer from outside. Computations of the mid-layer distribution of diffuse light with latitude are made for various combinations of the single-scattering albedo a and the asymmetry factor g.

Curves with different F can in practice be matched if a or g are adjusted. Earlier analyses of observed data based on a model with $F=1$ may have led to an underestimate of a and/or g.

Key words: interstellar dust — diffuse galactic light

1. Introduction; Choice of Model

The first measurements of the diffuse galactic light were made and interpreted by Henyey and Greenstein (1941). It was realized from the start that the intensity of the diffuse galactic light and its dependence on latitude contain important clues about the albedo a of the interstellar dust grains and about the asymmetry factor g of their scattering pattern. In spite of the fact that the optical depth of the dust layer perpendicular to the galactic plane is <1, we have essentially a problem of multiple scattering, for at low latitudes we look through layers of considerable depth.

The presence of multiple scattering means that we cannot hope to infer the scattering pattern in great detail from the measurements. Also the accuracy of the measurements should not be overrated because of difficulties of calibration and of removing all other sources of diffuse skylight. For this reason it is advisable to be content with model fitting, each model being characterized by only a few parameters.

Most papers on the subject so far have made the following assumptions:

1. Isotropic sources (stars) are distributed symmetrically in plane layers of infinite extent parallel to the galactic plane. Hence the source-density is a function of only one variable, z, the distance from the galactic plane.
2. Interstellar dust grains also have a plane-stratified distribution, so that their number-density is again a symmetric function of z only.
3. The sun, i.e. our observing position, is in the mid-layer plane.
4. The properties of the dust grains do not change with z and their scattering pattern is the Henyey-Greenstein function, fully characterized by the two parameters a and g.
5. The ratio of dust to stars is the same at all z, so that each has the same distribution with z.

In the present paper we maintain assumptions 1–4, and we relax assumption 5. Admitting arbitrary z-distributions of stars and dust (so that assumption 5 is dropped altogether) would lead to rather complicated calculations and would introduce too much freedom into the fitting procedure (Mathis, 1973). There is some evidence that the dust is confined to a systematically thinner slab than the stars (see Section 3.1). We have, therefore, replaced assumption 5 by the new one:

5*. The dust is confined to a slab of limited thickness. The stars inside this slab represent a fraction F of the total number of stars and are distributed in the same way with z as the dust. The stars outside the dust slab represent a fraction $1-F$ of the total number of stars. They are divided in equal numbers above and below the slab but have an otherwise arbitrary z-distribution.

This clearly is another unrealistic assumption, but it has the advantage of introducing only one additional parameter and of including assumption 5 as a possibility. Thus, by a small extension of work already done, a first assessment may be made of the way in which the conclusions drawn from the observed diffuse galactic light may be influenced by different distributions of stars and dust.

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2. Calculation of Midlayer Brightness Distribution

2.1. Homogeneously Embedded Sources Only

It is always possible to transform the vertical z-scale into a τ-scale, which ranges from $-\frac{1}{2}b$ to $+\frac{1}{2}b$, with $\tau=0$ at the midlayer plane. On this τ-scale the model consists of a homogeneous dust layer of total depth b with homogeneously embedded stars as primary light sources. We shall also measure the horizontal coordinates in terms of the mean free light path and denote the flux emitted by all primary sources in a unit volume per unit solid angle by A. Let $\mu=\cos\theta$, where θ is the angle between the line of sight and the galactic pole.

We then observe at midlayer:

a) the intensity of unscattered starlight (zero order):

$$AI_s^{\text{hom}}(b,\mu)=A[1-\exp(-\tfrac{1}{2}b/\mu)];$$

b) the intensity of diffuse light (orders 1 to ∞ combined):

$$AI_d^{\text{hom}}(b,a,g,\mu).$$

Values of the function I_d^{hom} are available for several combinations of a, g, b (van de Hulst and De Jong, 1969) and are contained in Table 1 on the lines $F=4/4$.

2.2. Surface-layer of Sources

In the opposite extreme the stars are only outside the dust slab. It then does not matter how far from the slab these stars stand. We may therefore imagine them all concentrated into a homogeneous surface-layer just above the slab and an identical surface-layer just below the slab. The situation in which a surface-layer of sources exists at one side, say above, emitting into direction μ the intensity $1/(2\mu)$, is familiar in the theory of multiple scattering in planetary atmospheres. In agreement with earlier papers (e.g. van de Hulst, 1971) we shall designate this situation by the symbol N. The incident flux per unit area of the slab is π.

The mid-layer radiation field is found as a byproduct of the doubling method even if the main interest is in finding the emergent fields at top or bottom. We write the intensity at mid-layer in this standard problem:

upwelling radiation $U(b,a,g,N,\mu)$

with $\mu=$ cosine of angle with upward normal,

downwelling radiation $D(b,a,g,N,\mu)$

with $\mu=$ cosine of angle with downward normal.

By this definition, μ is reckoned from 0 to 1 in both hemispheres.

Putting a normalized surface-layer of sources N both above and below the slab we obtain the mid-layer intensity distribution $U+D$, identical in both hemispheres. If the emission from the surface layers amounts to B times the normal N layer, the final intensity observed in the mid-layer is:

starlight and diffuse light combined (orders 0 to ∞):

$$B[I_s^{\text{sur}}(b,\mu)+I_d^{\text{sur}}(b,a,g,\mu)]$$
$$=B[U(b,a,g,N,\mu)+D(b,a,g,N,\mu)];$$

starlight only (zero order):

$$BI_s^{\text{sur}}(b,\mu)=(B/2\mu)\exp(-b/2\mu).$$

The diffuse light can be found by subtraction.

Among the output of older computations, made for testing the doubling method, we had some with the radiation fields U and D printed out. In several other combinations of parameters this output had not been made and new integrations had to be performed. This was done by an abbreviated method but with sufficient care to make sure that errors larger than 1% were avoided in all directions.

2.3. Embedded and Surface Sources Combined

The radiation fields derived in the preceding subsections may be added linearly. This gives the observed light in the mid-layer:

starlight only: $I_s=AI_s^{\text{hom}}+BI_s^{\text{sur}}$
diffuse light only: $I_d=AI_d^{\text{hom}}+BI_d^{\text{sur}}$

The choice of the constants A and B is still open. We wish in first instance to compare models in which the total amount of dust and the total number of stars are kept constant. The first requirement gives $b=$ constant. In order to satisfy the second requirement we note that the intensity of starlight that would arrive at mid-layer in the absence of extinction from the homogeneous half slab is $Ab/(2\mu)$ and from one surface-layer is $B/(2\mu)$. These must be in the ratio of F to $1-F$. We adopt therefore:

$$A=F/b \quad \text{and} \quad B=1-F.$$

This means that the combined intensity shed by the stars inside and outside the dust slab to an observer in the midplane is in the absence of extinction $1/(2\mu)$. It also means that the unit of intensity adopted in all calculations is the (smoothed out) intensity of starlight that an outside observer, looking perpendicularly to the galactic plane, would see in the absence of any scattering or extinction.

The values thus computed are shown in Table 1 for several combinations of the parameters a, g and b. Some of our results can be compared with those obtained by Matyagin and Rozhkovski (1972). These authors use a somewhat unusual phase function. For the choice of parameters $b=0.25$, $F=0.5$, $a=1$ we should compare our results with asymmetry factor $g=0.5$ to their results with phase-parameter $x_1=0.932$. Agreement is within 3%, apart from a factor 2 in the normalisation.

Table 1a. Brightness of diffuse galactic light, $I(\frac{1}{2}b, a, g, \mu, F_*)$ observed at midlayer in a model specified by parameters a, g, μ, F_* and $b=0.25$

g	a	F_*	$\mu=0.00$	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.70	0.90	1.00
0.00	0.40	4/4	0.584	0.396	0.312	0.256	0.216	0.188	0.164	0.148	0.132	0.120	0.088	0.072	0.064
		3/4	0.533	0.371	0.294	0.242	0.204	0.178	0.155	0.140	0.125	0.114	0.084	0.068	0.061
		2/4	0.481	0.347	0.275	0.227	0.193	0.167	0.147	0.132	0.118	0.108	0.080	0.065	0.058
		1/4	0.430	0.322	0.257	0.213	0.181	0.157	0.138	0.124	0.111	0.107	0.075	0.061	0.054
		0/4	0.378	0.297	0.238	0.198	0.169	0.146	0.129	0.116	0.104	0.096	0.071	0.057	0.051
0.00	0.80	4/4	1.352	0.920	0.724	0.592	0.500	0.432	0.380	0.340	0.308	0.280	0.208	0.164	0.148
		3/4	1.237	0.862	0.681	0.559	0.472	0.409	0.360	0.322	0.292	0.266	0.197	0.156	0.141
		2/4	1.123	0.805	0.638	0.526	0.445	0.385	0.340	0.304	0.275	0.251	0.186	0.147	0.133
		1/4	1.008	0.747	0.595	0.493	0.417	0.362	0.319	0.286	0.259	0.237	0.175	0.139	0.126
		0/4	0.893	0.689	0.552	0.460	0.389	0.338	0.299	0.268	0.242	0.222	0.164	0.130	0.118
0.00	0.90	4/4	1.588	1.076	0.848	0.692	0.584	0.508	0.444	0.400	0.360	0.328	0.240	0.192	0.172
		3/4	1.454	1.009	0.799	0.653	0.552	0.480	0.421	0.378	0.341	0.311	0.228	0.182	0.164
		2/4	1.319	0.942	0.749	0.614	0.520	0.452	0.397	0.357	0.321	0.294	0.216	0.172	0.155
		1/4	1.185	0.874	0.700	0.574	0.487	0.424	0.374	0.335	0.302	0.277	0.203	0.162	0.147
		0/4	1.050	0.807	0.650	0.535	0.455	0.396	0.350	0.313	0.282	0.260	0.191	0.152	0.138
0.00	1.00	4/4	1.840	1.248	0.984	0.804	0.680	0.588	0.516	0.460	0.416	0.380	0.280	0.224	0.200
		3/4	1.686	1.171	0.924	0.758	0.643	0.556	0.488	0.436	0.393	0.360	0.266	0.212	0.190
		2/4	1.532	1.094	0.865	0.712	0.605	0.524	0.461	0.411	0.371	0.340	0.252	0.200	0.180
		1/4	1.377	1.016	0.805	0.666	0.568	0.491	0.433	0.387	0.348	0.320	0.237	0.188	0.169
		0/4	1.223	0.939	0.745	0.620	0.530	0.459	0.405	0.362	0.325	0.300	0.223	0.176	0.159
0.50	1.00	4/4	2.212	1.452	1.116	0.888	0.728	0.608	0.520	0.448	0.388	0.340	0.212	0.144	0.128
		3/4	2.017	1.370	1.060	0.850	0.699	0.587	0.505	0.437	0.381	0.334	0.212	0.145	0.128
		2/4	1.822	1.288	1.003	0.812	0.669	0.567	0.490	0.427	0.374	0.329	0.213	0.147	0.128
		1/4	1.627	1.206	0.947	0.773	0.640	0.546	0.475	0.416	0.367	0.323	0.213	0.148	0.128
		0/4	1.432	1.124	0.890	0.735	0.610	0.525	0.460	0.405	0.360	0.317	0.213	0.149	0.128

Table 1b. Brightness of diffuse galactic light, $I(\frac{1}{2}b, a, g, \mu, F_*)$ observed at midlayer in a model specified by parameters a, g, μ, F_* and $b=0.50$

g	a	F_*	$\mu=0.00$	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.70	0.90	1.00
0.00	0.40	4/4	0.472	0.416	0.362	0.316	0.280	0.248	0.224	0.204	0.186	0.172	0.130	0.106	0.096
		3/4	0.420	0.379	0.334	0.293	0.260	0.230	0.208	0.190	0.173	0.160	0.122	0.099	0.090
		2/4	0.369	0.342	0.306	0.271	0.240	0.212	0.193	0.176	0.161	0.149	0.113	0.092	0.084
		1/4	0.317	0.304	0.278	0.248	0.220	0.194	0.177	0.162	0.148	0.137	0.105	0.085	0.077
		0/4	0.265	0.267	0.250	0.225	0.200	0.176	0.161	0.148	0.135	0.125	0.096	0.078	0.071
0.00	0.80	4/4	1.210	1.066	0.930	0.810	0.714	0.636	0.574	0.520	0.476	0.440	0.334	0.270	0.246
		3/4	1.086	0.974	0.858	0.750	0.661	0.590	0.533	0.484	0.443	0.410	0.31	0.252	0.230
		2/4	0.961	0.882	0.785	0.690	0.607	0.545	0.492	0.448	0.411	0.380	0.290	0.234	0.214
		1/4	0.837	0.790	0.713	0.630	0.554	0.499	0.451	0.411	0.378	0.349	0.267	0.216	0.197
		0/4	0.712	0.698	0.640	0.570	0.500	0.453	0.410	0.375	0.345	0.319	0.245	0.198	0.181
0.00	0.90	4/4	1.466	1.290	1.124	0.980	0.864	0.770	0.694	0.630	0.576	0.532	0.404	0.326	0.298
		3/4	1.317	1.181	1.043	0.911	0.802	0.715	0.646	0.586	0.537	0.496	0.377	0.305	0.279
		2/4	1.169	1.072	0.962	0.843	0.740	0.660	0.597	0.543	0.498	0.460	0.350	0.283	0.259
		1/4	1.020	0.963	0.881	0.774	0.677	0.604	0.549	0.499	0.459	0.423	0.323	0.262	0.240
		0/4	0.871	0.854	0.800	0.705	0.615	0.549	0.500	0.455	0.420	0.387	0.296	0.240	0.220
0.00	1.00	4/4	1.762	1.550	1.350	1.178	1.038	0.926	0.832	0.756	0.692	0.638	0.486	0.392	0.356
		3/4	1.588	1.420	1.250	1.094	0.962	0.860	0.773	0.703	0.644	0.594	0.453	0.366	0.333
		2/4	1.414	1.291	1.150	1.009	0.887	0.793	0.714	0.650	0.596	0.551	0.421	0.340	0.309
		1/4	1.239	1.161	1.050	0.925	0.811	0.727	0.654	0.596	0.548	0.507	0.388	0.313	0.286
		0/4	1.065	1.031	0.950	0.840	0.735	0.660	0.595	0.543	0.500	0.463	0.355	0.287	0.262
0.50	0.90	4/4	1.668	1.436	1.224	1.042	0.894	0.774	0.676	0.594	0.526	0.468	0.308	0.214	0.180
		3/4	1.497	1.318	1.139	0.980	0.846	0.734	0.645	0.568	0.507	0.454	0.304	0.214	0.182
		2/4	1.327	1.199	1.055	0.918	0.797	0.694	0.613	0.542	0.488	0.439	0.300	0.215	0.184
		1/4	1.156	1.081	0.970	0.855	0.749	0.653	0.582	0.516	0.469	0.425	0.296	0.215	0.185
		0/4	0.985	0.962	0.885	0.793	0.700	0.613	0.550	0.490	0.450	0.410	0.292	0.215	0.187
0.50	1.00	4/4	2.006	1.726	1.472	1.252	1.074	0.930	0.812	0.714	0.632	0.562	0.368	0.256	0.216
		3/4	1.807	1.587	1.372	1.174	1.012	0.882	0.774	0.686	0.612	0.544	0.363	0.256	0.217
		2/4	1.609	1.449	1.271	1.096	0.950	0.834	0.736	0.657	0.591	0.526	0.357	0.255	0.219
		1/4	1.410	1.310	1.171	1.018	0.887	0.785	0.698	0.629	0.571	0.508	0.352	0.255	0.220
		0/4	1.211	1.171	1.070	0.940	0.825	0.737	0.660	0.600	0.550	0.490	0.346	0.254	0.221

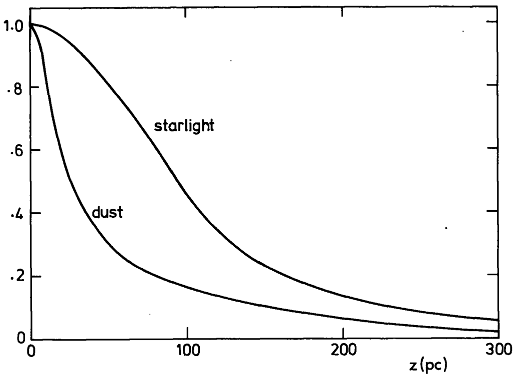

Fig. 1. Representative distributions of starlight and dust with distance z from the galactic plane

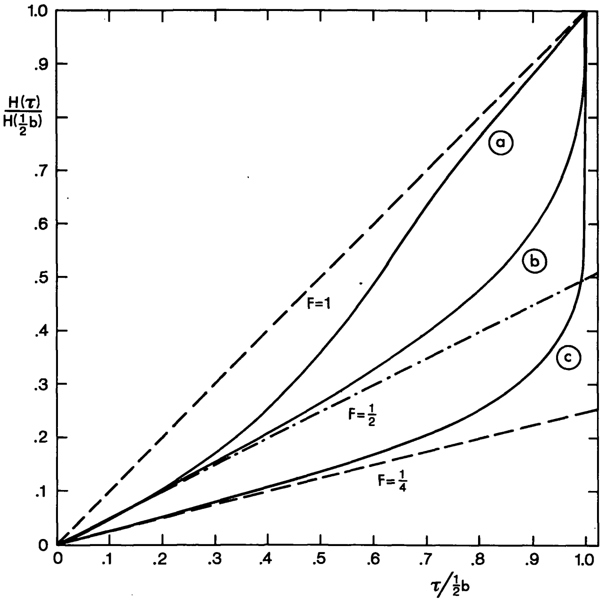

Fig. 2. The relative distribution of stars and dust is shown here by plotting cumulative fractions of starlight (ordinates) against the cumulative fraction of dust (abscissa)

3. Comparison with Observations

3.1. Range of Eligible Values of the Parameter F

In Figure 1 we show the vertical starlight distribution derived from Schmidt (1963) and the dust distribution according to Neckel (1966), both normalized to 1 at $z=0$. The dust distribution clearly is narrower but has a long tail. The transformation to a uniform dust layer is carried out as follows.

Let the extinction coefficient in the galactic plane be k and adopt k^{-1} as the unit of length in all coordinates. In these units, let $f(z)$ be the extinction coefficient at level z. Then $f(0)=1$. The function $f(z)$, or its integrated function, the optical depth $\tau(z)=\int_0^z f(z')dz'$, completely characterizes the dust distribution. The optical thickness of half the galactic dust layer is $\frac{1}{2}b=\tau(\infty)$.

Still using the same units, let $g(z)$ be the number of stars per unit volume at level z and $G(z)=\int_0^z g(z')dz'$ the integrated number per unit area in a column between the galactic plane and level z.

Upon compressing the dust to a homogeneous layer, i.e. adopting the vertical τ-scale instead of the z-scale we have to compress the stellar distributions accordingly. For simplicity we assume that extinction is nowhere absent so that $\tau(z)$ is an increasing function with non-zero derivative $d\tau/dz=f(z)$ all the way. The stellar column density to a certain level then should remain unchanged:

$$H(\tau)=\int_0^\tau h(\tau')d\tau'=G(z),$$

or upon differentiation:

$$h(\tau)=g(z)/f(z).$$

Here the argument τ at the left side must be read as $\tau(z)$.

This transformation leaves the intensity distribution of both the starlight and the diffuse light unchanged: the distributions found in the first model at level z are found in the compressed model at level $\tau(z)$. The paradox that this vertical compression would make a slanting line into a curve is resolved by considering that the comparison should be made between a path that is straight in the original model and another path that is straight, with the same μ, in the compressed model.

The relative distribution of stars and dust can conveniently be examined in the representation of Figure 2. The abscissa $\tau/\frac{1}{2}b$ is the cumulative fraction of dust from the galactic plane to a certain level z and the ordinate is the corresponding cumulative fraction of star light. Curve a corresponds to the z-distributions of Figure 1. If we choose gaussian approximations $g(z)=\exp\{-(z/k_*)^2\}$ and $f(z)=\exp\{-(z/k_d)^2\}$, then Curve b corresponds to $k_d/k_*=0.50$ and Curve c to $k_d/k_*=0.25$. The model introduced by assumption 5* in Section 1 corresponds to a straight line in the figure. These lines are shown for 3 values of F. Clearly, if this model is any good at all, a value of F between $\frac{1}{2}$ and 1 seems most appropriate.

The observed latitude distribution of direct starlight may be used as a further check because it depends both on the z-distribution of starlight and of dust. In the model corresponding to assumption 5*, the distribution $I_s(b, F, \mu)$ seen from the mid-layer plane, may be directly calculated. We compared this distribution for various combinations with the observed distribution of starlight in the visual bandpass (Roach and Megill, 1961). The conclusion was that no further restrictions in the choice of parameters could be made. For low F-values there is a dip at $\mu=0$ in the theoretical starlight distribution.

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3.2. The Diffuse Galactic Light

Figure 3 shows several examples of the computed distribution of diffuse galactic light from equator to pole according to the numbers given in Table 1a. Since the same unit of intensity has been maintained, these curves can be directly intercompared. The net effect of a value of F which is less than one is to lower the intensity and to broaden the intensity distribution. But the figure also shows that a similar change is brought about by changing from an elongated phase function to more isotropic scattering (i.e. to smaller g). Therefore, we cannot hope to determine F separately from g on the basis of such observations.

This conclusion is confirmed if we follow the reduction procedure used in earlier discussions (van de Hulst and De Jong, 1969), which consists of subtracting the level reached at $\mu=0.5$ (galactic latitude 30°) but otherwise maintaining the intensity scale. Figure 4 shows some sample results, in which curves for matching combinations of parameters have been drawn together. Figure 4a and b show for two combinations of a and b a close match between the pairs $g=0.5$, $F=0.5$ and $g=0$, $F=1$. Hence the effect of putting half the number of stars outside the dust slab is virtually cancelled by taking $g=0.5$ instead of $g=0$.

Because the b-values are small, the intensity drop with albedo is about linear for all values of F. Therefore, also a lower albedo tends to give a broader distribution of diffuse light. As a result, a high albedo and low F value can give about the same diffuse light distribution as a low albedo and high F-value. A matching combination of this type is illustrated in Figure 4c.

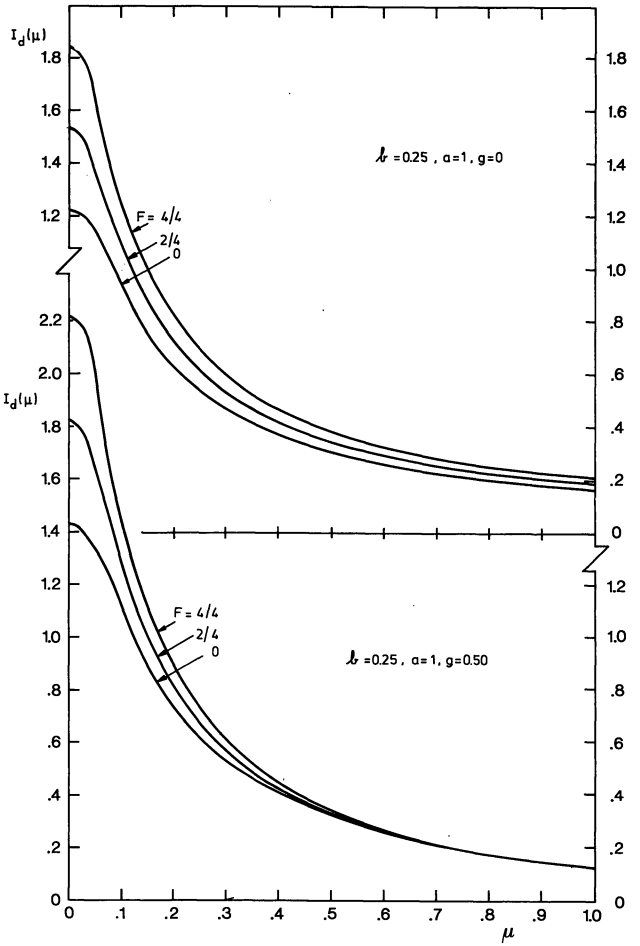

Fig. 3. These two examples show the full range over which the intensity distribution of the diffuse galactic light with $\mu=\sin$ (galactic latitude) changes if the assumption about the stellar distribution is varied from $F=1$ to $F=0$

4. Conclusions

The conclusion from the preceding comparisons is clear. If it is possible to obtain a satisfactory match to the observational data by means of a model with equal distributions of gas and dust ($F=1$)—and the earlier papers led to the conclusion that this is possible—then it is also possible to obtain a satisfactory match by means of a model in which the stars extend beyond the dust layer (say, $F=0.75$ or $F=0.5$). Such a match requires that g is adjusted to higher value, or a to a higher value, or both.

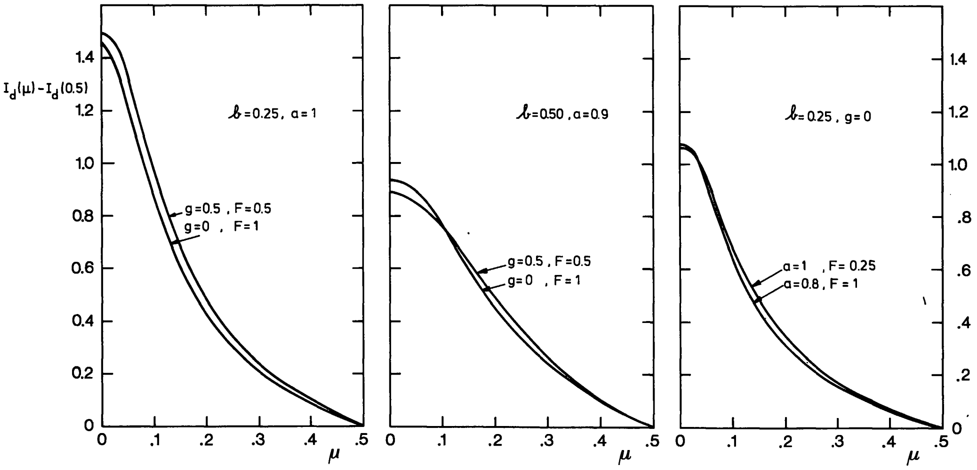

Fig. 4a—c. The three examples in this figure demonstrate that almost identical diffuse light distributions below 30° latitude can be obtained from models with different values of F by an adjustment of either g or a

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Figure 4 gives some quantitative examples of such adjustments but the computations presented in this paper are not sufficiently complete to derive the rules for these adjustments in detail.

Since we have found in Section 3.1 that the most appropriate value of F is somewhere between $\frac{1}{2}$ and 1, we may infer that the most likely values of a and g following from the observed diffuse galactic light are somewhat higher than has been usually assumed (e.g. Witt, 1968; van de Hulst and De Jong, 1969).

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