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The local contribution to the microwave background radiation

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Abstract The observed microwave background radiation (MBR) is commonly interpreted as the relic of an early hot universe, and its observed features (spectrum and anisotropy) are explained in terms of properties of the early universe. Here we describe a complementary, even possibly alternative, interpretation of MBR, first proposed in the early $20^{\rm th}$ century, and adapt it to modern observations. For example, the stellar Hipparcos data show that the energy density of starlight from the Milky Way, if suitably thermalized, yields a temperature of ∼2.81 K. This and other arguments given here strongly suggest that the origin of MBR may lie, at least in a very large part, in re-radiation of thermalized galactic starlight. The strengths and weaknesses of this alternative radical explanation are discussed.

Key words: Galaxy: stellar content — (cosmology:) cosmic microwave background — cosmology: observations

1 INTRODUCTION

In 1926, Eddington made an order of magnitude calculation in which he estimated the total background radiation from stars in the Galaxy by assuming a population of only 2000 stars of apparent bolometric magnitude $m = 1.0$. He arrived at an energy density of starlight of around 7.67×10^{-13} erg cm^{-3}. If equated to a blackbody equilibrium distribution, this worked out to a temperature of ~ 3 K. Eddington (1926) identified this as the "temperature of interstellar space." An earlier calculation by Guillaume (1896) had led to a similar result for temperature ($\sim 5 - 6$ K). Both he and Eddington had felt that the actual temperature might be somewhat higher than their values when estimated in this way.

First we note that the observed microwave background radiation (MBR) is a very close approximation to a blackbody of temperature of $T_0 = 2.726$ K. This radiation, *a priori*, could have three possible sources, without excluding other possible interpretations:

(1) Cosmological radiation (CR in brief) as the fossil radiation from an early hot universe, cooled adiabatically by expansion, as first proposed by Alpher & Herman (1948), and later as definitely accepted in the reference frames of the "standard" cosmological models;

(2) Direct radiation (DR) from galaxies and stars, eventually scattered by dust, and:
(3) Reradiated radiation (RR), i.e. stellar radiation in the Galaxy or galaxies which is absorbed and reradiated by dust (i.e. non–scattered). A systematic historical account of various attempts to estimate the temperature of cosmic radiation background along those lines was given by Assis & Neves (1995).

It is interesting to note that although George Gamow was not a co-author of the paper (Alpher & Herman 1948) predicting the existence of a relic background, he later was an enthusiastic proponent of the interpretation. His own estimate of the thermal temperature of the background increased progressively through a sequence of values from 7 K to 50 K. As is now realized, the standard model with its given dynamical parameters is not able to predict the present temperature of this background. The observed value of 2.726 K is taken as an additional parameter of the theory.

The CR, as is well known, is not related to starlight or to any population of discrete sources. The MBR according to CR would have existed even in a universe without any star formation. The CR completely ignores any possible influence of starlight, be it scattered or reradiated. The second alternative (DR) seems unworkable as its background radiation is quite small in both microwave and infra-red (IR), compared to the observed MBR, and clearly anisotropic and different in its spectrum from blackbody radiation. However, as we shall soon see, a plausible case can be made for the third alternative, that of RR. This alternative does not call for any cosmological relic radiation and was indeed suggested by several authors without reference to cosmology. We have already mentioned Guillaume (1896) and Eddington (1926), but Regener (1933), Nernst (1938) and Born (1954a,b) made similar estimations, as described by Assis & Neves (1995).

The discovery of small scale inhomogeneities in the MBR by the *Cosmic Background Explorer* (*COBE*) and the subsequent fine measurements of their power spectrum by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) has provided momentum to the CR option with detailed explanations of the observed features. However, as mentioned above, the actual temperature of the MBR cannot be predicted: it is taken as a free parameter arbitrarily set at its present value. An alternative way of stating this is to say that as yet, the photon to baryon number ratio cannot be deduced from any calculations pertaining to the "early universe."

By contrast, in the RR contribution to the MBR, the temperature of the background can be derived from the given data on the stellar background, without any recourse to a cosmological model. It is known for example that if all the observed helium were produced in stars, the resulting starlight would have an energy density equaling that of a blackbody of 2.7 K (see for example, Hoyle & Wickramasinghe 1968; Hoyle et al. 2000). This, of course, suggests an astrophysical character for the MBR rather than a cosmological one. In this paper we will elaborate on this idea further.

In Section 2 we discuss the RR version, starting with its source function. Using the method for stellar atmospheres we estimate its temperature. This is followed by the consideration of interstellar dust and how it absorbs and reradiates the stellar radiation. Then in Section 3 we discuss the process of thermalization by the dust grains which are needle shaped. Section 4 deals with observational checks including those provided by *COBE* and *WMAP*. In Section 5 we discuss the Sunyaev-Zeldovich (S-Z) effect and how it may help distinguish between our model and the standard model of MBR. Finally in Section 6 we conclude by proposing further studies to check on the viability of the RR paradigm.

2 THE RR VERSION

2.1 The "Source-function"

In an earlier paper referred to henceforth as Paper I, Pecker & Narkikar (2006) had calculated (see the Appendix) the flux F of starlight received at the Earth, based on the extensive Hipparcos data stored in the CDS archives at Strasbourg.

That flux is obviously highly anisotropic. From it, to derive the local temperature of the medium, we need to consider a transfer problem, similar to the process that dominates stellar atmospheres. We shall therefore use the classical context of radiative equilibrium, as described in several standard textbooks on stellar structure. In the radiation transfer equation, we shall neglect the so-called "scattering term," which is important at short wavelengths, as it is not related to the "reradiation," whereas the reradiation is only important at the long wavelengths (microwaves). We can write, in a plane-parallel geometry

$$dI_\nu/dh = -\kappa_\nu I_\nu + B_\nu \,, \tag{1}$$

where we relate the optical depth τ_ν to the vertical height h by $k_\nu dh = -d\tau_\nu$ with k_ν being the opacity of matter with respect to radiation of frequency ν. The "source-function" B_ν can be taken to be the Planck function. B_ν is the function of the local blackbody temperature at height h, which we denote by $T(h)$. Note that although the source function B_ν in the interstellar medium (ISM) is by definition isotropic, the intensity I_ν of the radiation coming from the Galaxy is indeed obviously anisotropic. In that particular case, if, at a given location in the medium, we denote the mean intensity of radiation averaged over all directions by $\langle I_\nu \rangle$, then the conservation of radiative flux gives the result

$$\langle I \rangle = \int_0^\infty \langle I_\nu \rangle \kappa_\nu d\nu = \int_0^\infty B_\nu(T) d\nu = B(T) \,. \tag{2}$$

The dominant part of the integral on the left-hand side is the one contributed by the short wavelengths and visible parts of the spectrum; there the opacity of the ISM is very weak, and we can consider that the intensity of the radiation coming from the Galaxy is identical with what we observe at the Earth, with the radiation flux resulting from observations reported in the preceding paragraph.

The relation of the flux F as observed with the intensity $\langle I \rangle$ is simple and is derived from an integration over the whole sky as follows

$$F_0 = (1/4\pi)\left(\int_0^{2\pi} \int_0^{\pi} \langle I(\theta) \rangle \cos\theta \quad \sin\theta \; d\theta \; d\phi \right). \tag{3}$$

Within this framework, the real value of the flux F_0, which is an average value of the intensity, is smaller than the value of the flux F from Galactic radiation, which is the average value of the intensity of only a small fraction of the sky, namely the Milky Way, with the rest of the sky being almost dark.

The results of the analyses of the Tycho 2 catalogue are (see Appendix):

$$\begin{aligned} & F = \; 1.782 \times 10^{-2}\ \mathrm{erg\ cm^{-2}\ s^{-1}} > F_0, \ \text{using bolometric corrections} \\ \text{or} \quad & F = \; 1.71\ \mathrm{erg\ cm^{-2}\ s^{-1}}, \ \text{using multicolor data}\,. \end{aligned} \tag{4}$$

Assuming that the radiation was coming isotropically from all directions, the equilibrium temperature of dust in the medium would be

$$T_{\rm eff} = [F/\sigma]^{1/4} = 4.21\ \mathrm{K}\,, \quad \text{or} \quad T_{\rm eff} = 4.17\ \ \mathrm{K}\,, \tag{5}$$

where σ is the Stefan-Boltzmann constant. This is the "effective temperature," as in stellar atmospheres, i.e. not the local temperature, but the temperature of radiation, with both being equal to each other only if the radiation field is isotropic.

However, *the distinctive property of the stellar radiation flux is that it is not isotropic*. The bulk of it comes from the plane of the Milky Way. The solid angle Ω subtended by the distribution of stars in the Milky Way is not 4π. A dust grain does not receive radiation from all directions, hence a large part of the dust grain does not receive radiation. The flux F_0 actually received by each cm^2 of a grain (be that square centimeter in light or in shadow) is, on the average,

$$F_0 = (\Omega/4\pi)F \,. \tag{6}$$

In such a situation, a dust grain is not heated by the stellar flux over all its surface but only on the fraction $\Omega/4\pi < 1$, but it reaches an equilibrium temperature. The rest of the grain is not heated, but radiates. Thus it *isotropically* radiates the blackbody radiation at the temperature $T_0 < T_{\mathrm{eff}}$, and the isotropic radiated flux is

$$F_0 = \sigma T_0^4 = (\Omega/4\pi)F\,, \tag{7}$$

hence

$$T_0 = (F_0/\sigma)^{1/4} = (F\Omega/4\pi\sigma)^{1/4}\,. \tag{8}$$

What is the value of Ω? As determined by us from the *COBE* images (Mather et al. 1994), we can consider the Milky Way as a band with width 5° to 15°, on both sides of the celestial equator. It fills about 1/9 to 1/3 of the whole sky. This means that the local average flux transferred into thermal energy is only a fraction $q = \Omega/4\pi = 1/9$ to $1/3$ of the flux F, when considered per square centimeter of grain surface. This results in a reduction of the local thermal temperature of the grain, with respect to the temperature equivalent to the incident energy, by the factor

$$q^{1/4} \approx 0.58 \text{ to } 0.76\,, \tag{9}$$

thus bringing it down, from Equation (8), to

$$T_0 q_{\mathrm{eff}}^{1/4} = 2.42 \text{ K to } 3.20 \text{ K}\,. \tag{10}$$

An “average value” corresponding to a Milky Way with a temperature of ten degrees on each side of the Galactic plane would be

$$\langle T_0 \rangle \approx 2.81 \text{ K}\,. \tag{11}$$

An analogy with the local radiation field in the solar photosphere can help: there the effective temperature is of the order of ≈ 5770 K and the local “surface” temperature is of the order of ≈ 4670 K.

2.2 The Opacity Term

In the RR case, we assume that, given an effective thermalization of dust, a similar situation will occur for the RR, i.e. a local isotropy. As the re-radiation by the interstellar dust occurs predominantly in the microwave band, given the above value of T_0, it can produce a completely isotropic blackbody radiation with temperature T_0 in the vicinity of the Earth. Therefore, the “source-function” of the equation for the radiation transfer is $B_{\nu\nu}(T_0)$ with $B_\nu(T)$ being the Planck-function. For this blackbody radiation to be as intense as that within an opaque furnace, i.e. that of an undiluted blackbody, it requires the re-emitting medium to be sufficiently opaque in that band. If the medium is not opaque, but has an optical depth τ, then the temperature of the microwave radiation field at the Earth will be reduced by the factor $(1 - e^{-\tau})^{1/4}$. For τ of the order of 10, it would be reduced by a factor of the order of 10^5. Clearly for the above explanation to be viable, the optical depth must largely exceed unity in the microwave spectral domain. As the late Fred Hoyle once put it: the situation is like that of a mountaineer lost in heavy fog, which produces a very short range of visibility. The anisotropic landmarks that would have helped him to find the right track are obscured by this low visibility.

Also, in a local explanation, the absorbing dust must be very close, perhaps not far from the galactic center. In any case, it has to be located within the Local Group.

What type of absorbing matter can be viable? What are the dust particles in the galactic environment that produce such a “microwave fog?”

These dust particles will be such that for them the grey approximation would be valid. Above, we have computed the equilibrium temperature arising from the radiation energy flux of all stars in the Galaxy at a point in the solar system (where we happen to be). We know more or less the absorption coefficient of dust in the visible and ultraviolet parts of the spectrum and its density distribution in the galactic surroundings. For the purposes of our discussion, let us assume that it is non zero, so the starlight will therefore be (partially) absorbed and reradiated. If this process is allowed to go on many times during the lifetime of the Galaxy, then an equilibrium temperature T_0 such as that determined above will be reached. The actual time scale for this to occur is estimated as follows.

The interstellar matter would reach this temperature only if the lifetime of the region where the interaction takes place is sufficiently long. Since the Galactic age is of the order of 10 Gyr, the time taken for thermalization can be as high as 1 Gyr. Taking the Galactic dimension to be ∼30 kpc, light takes $\sim\ 10^5$ yr to traverse it once. Thus, in a period of 10^7 yr, the starlight will get absorbed and re-emitted ∼100 times. So the Galactic time scale of 10^{10} yr is more than adequate to assure thermalization.

2.3 The Dust Absorbing in the Microwave Domain

The conventional candidates for interstellar absorption, for example atoms or molecules of various kinds, and dust, e.g. in the form of carbonaceous grains, have been thoroughly discussed in the context of the galactic environment. None of these serve our purpose of providing opacity peaking in the microwave region. However, the dust made of metallic whiskers discussed by Hoyle & Wickramasinghe (1988) will serve the purpose adequately.

Metallic whiskers form when the metals synthesized in supernovae are ejected as vapours, which cool down to condense in solid form. Laboratory experiments (Sears 1956; Nabarro & Jackson 1958; Dittmar & Neumann 1958; Lefevre 1967) show that these condensates are not spherical but are shaped like whiskers. Typically a whisker may be 0.5–1.0 mm long and around 10^{-6} cm in cross-sectional diameter. Absorption of light by such whiskers peaks at mm-wavelengths, being moderate in the optical band and much less in the radio wavelengths. For details see Hoyle & Wickramasinghe (1988), Wickramasinghe & Hoyle (1994) and Wickramasinghe (2006). Whiskers swept away by the shock wave generated by a supernova and propelled by radiation pressure can reach even beyond the parent galaxy.

Whiskers have earlier been invoked by Narlikar et al. (2007) to explain the origin of the microwave background in the *Quasi-Steady State Cosmology* (QSSC) (see also: Hoyle et al. 2000). According to QSSC, the universe has no beginning; it expands in a long term exponential way together with short term oscillations, as exemplified by the following scale factor

$$S(t) = \exp(t/P) \times [1 + \eta \cos(2\pi t/Q)]\,, \tag{12}$$

where $P\ =\ 20\,Q$, and η has a magnitude less than unity. Thus this model is non-singular. It is argued that new matter is produced at the beginning of each cycle when the scale factor is minimum; then this matter forms into stars, which evolve and eventually get extinguished. With typically $Q = 50\,$Gyr, this is possible in each cycle for all but very low mass stars. The relic starlight from all the previous cycles can be calculated and it is shown that the thermalization of this relic radiation leads to the observed MBR with a Planckian spectrum and power spectrum as observed by Bennett et al. (2003) and Bouchet (2006). The thermalization is done by metallic, i.e. mainly by carbon and iron, whiskers. The same whiskers in the intergalactic medium help reproduce the observed redshift-magnitude relation for Type 1A supernovae (Wickramasinghe & Wickramasinghe 2008; Narlikar et al. 2002). Other astrophysical evidence for whisker-dust has been discussed by Narlikar et al. (1997). The article by Fries & Steele (2008) gives a recent account of work on grain shapes, especially in the form of a whisker.

3 THERMALIZATION

While iron at cryogenic temperatures and in the form of long thread-like particles (whiskers) is likely to be the dominant source of opacity in the microwave region, carbon particles also in the form of whiskers considerably exceed the effect of iron at shorter wavelengths. This is both because a larger amount of carbon is produced by stars than iron, and because the absorption efficiency of carbon is greater at shorter wavelengths.

The value of mass absorption coefficient $Q_{\rm abs}$ for graphite whiskers is essentially constant for all wavelengths longer than ~ 1 mm, extending even to long radio wavelengths, and is ~ 0.33 for whiskers with diameter 0.01 μm and length ~ 1 mm, equivalent to an absorption coefficient of 10^5 cm^2 g^{-1}.

The great bulk of optical radiation that becomes subject to thermalization has been traveling for $10^6 - 10^7$ yr, and even more in the case of microwaves. The radiation incident on a carbon whisker has mostly been in propagation at least for this long and includes all the microwave radiation existing before. So, all such radiation has suffered very many scatterings and is exceedingly uniform in its energy density. For the moment we assume that radiation is entirely uniform, and quickly returns to uniformity after slight deviations. What we do not assume, however, is that the carbon whiskers, responsible for absorbing the starlight and re-emitting it into microwaves, are uniformly distributed. The carbon whiskers can be lumpy on the scale of clusters of stars. This means that the conversion of starlight to microwaves will start lumpily but each carbon whisker, wherever it is situated, finds itself in a radiation bath of uniform energy density, a radiation bath of which the major fraction already consists of microwaves from previous scatterings and the rest is mostly starlight still to be converted to microwaves. If all the radiation were microwaves, then the total flatness of $Q_{\rm abs}$ with respect to wavelength, through the range longward of ~ 1 μm, the temperature attained by the particles would simply be the standard microwave temperature, ~ 2.73 K as we know it to be. But because a fraction, say ten percent of the radiation, is at shorter wavelengths, the stellar component has a higher value of $Q_{\rm abs}$. This forces up the temperature of the grains, to a value of order

$$\sim (0.9 + 3^{1/4} \times 0.1) 2.73 \lesssim 2.82\ {\rm K},$$

with the second term in the brackets being contributed by the absorption of the starlight. Here we have assumed 0.1 of the total radiation is emitted at a wavelength that is shorter by a factor of 3, and that $Q_{\rm abs}$ is higher at these wavelengths. As the starlight is progressively absorbed with optical depth τ, the factor 0.1 in this equation should be replaced by $0.1e^{-\tau}$ and the factor 0.9 replaced by $(1 - 0.1e^{-\tau})$, so that the grain temperature varies according to

$$[1 + 0.1e^{-\tau}(3^{1/4} - 1)] 2.73\ {\rm K}.$$

Thus, as the starlight begins to be absorbed, the whisker temperature increases about 0.1 K higher and then returns to 2.73 K as the starlight is progressively absorbed.

The effect of τ being lumpily distributed on the scale of clusters of stars causes this process of producing a slight temperature rise followed by a fall back to 2.73 K to be correspondingly lumpy. *But what it does not do is to make the total radiated energy density lumpy at all.* Once the radiation energy density is totally uniform, this essential property is not changed by absorption and re-emission due to particles. Because of course each particle emits just as much energy as it absorbs - the total assembly of particles itself has only a negligible heat content - the particles do not store heat except in a very small amount. Thus, objections to this theory, based on lumpiness of the particles, are clearly invalid.

Since the emissivity of the particles has no wavelength dependence, they simply emit a Planck distribution $1/[\exp(\frac{h\nu}{kT}) - 1]$ at whatever value of T they may happen to have, according to the above temperatures, which may range up to about 2.82 K. But in general, they do not produce the Planck intensity $v^3[\exp(\frac{h\nu}{kT}) - 1]$. When T is raised slightly to 2.82 K, the intensity distribution is slightly diluted. So what is the outcome from this first absorption of the starlight? It is a uniform energy density of microwaves with a distribution approximately that of a blackbody at 2.73 K, but with some fluctuations in the details of the intensity curve with those details initially having a somewhat uneven distribution, to the extent that the carbon whiskers are distributed unevenly.

But now, with the starlight absorbed, and with the temperature of the particles everywhere the same, further absorption and re-emission inevitably generates the strict Planck distribution for 2.73 K. Only a few further absorptions are sufficient for this last step. It can be done with carbon whiskers, as Narlikar et al. (1976) suggested nearly four decades ago. However, the addition of even a small quantity of iron whiskers, with very high opacity at the center of the microwave distribution, would make this final step even more decisive.

We need to clarify that the MBR is produced in the QSSC by the astrophysical process of thermalizing starlight, but it is supposed to exist all over the universe. Thus according to the QSSC, the MBR temperature at the present epoch is 2.7 K everywhere in the universe. Although in the present model of RR we are using the same thermalizing agent as the QSSC, the MBR produced in this model is purely local. Taking metallic density to be $\sim 10^{-28}\mathrm{g\ cm^{-3}}$ in the Galaxy, we get an optical depth of ~ 10 across our local region extending to just beyond the Milky Way. Light takes $\sim 10^6$ yr to cross this region. Thus over $\sim 10^{10}$ yr, the presumed age of the Galaxy, light makes $\sim 10^4$ transits. With each transit giving $\tau = 10$, clearly there is ample opportunity for a very strict Planckian distribution to be established.

We see maser emission from some extragalactic sources, but we do not know how weakened they are in the microwave band. The resolving power of the microwave satellites like *COBE*, *WMAP* and even *PLANCK* is grossly insufficient to enable seeing microwave emitting galaxies; however, one could observe clusters of galaxies; these have been claimed to actually exist. Finding such sources would be a key observation that is in apparent contradiction with the present model. We will come back to that important point in the final discussion.

4 OBSERVATIONAL CONSTRAINTS

Spectroscopic observations like those by Swings & Rosenfeld (1937), McKellar (1941), Douglas & Herzberg (1941), etc., are strictly local and do not allow us to constrain this model or to make a distinction between CR and RR. Some authors have claimed to find, by the same method, temperatures higher than 3 K in the vicinity of some quasars with high redshift located near their parent galaxy. This argument is interesting but not decisive; the "local" contribution in those conditions might be quite different than in the case of our own Galaxy. However, direct and detailed studies of the MBR by *COBE* (Mather et al. 1990, 1994) and *WMAP* (Bennett et al. 2003; Bouchet 2006) do indeed allow us to make a distinction between RR and CR. The CR performs well in explaining these observations, but at the expense of assumptions about non-baryonic dark matter and dark energy, for which no independent direct evidence exists so far.

At the same time, we wish to draw attention to the features in the *COBE* and *WMAP* data which seem to have generally been ignored. In the domain relative to the Galactic plane, there exist (Fig. 1) two well-known conspicuous reddish-yellow regions and one conspicuous blue region, both of which are essentially not included in the power spectral analysis as published, but which are both located in the Galactic plane. The images of the whole sky are corrected for the Galactic non-blackbody (stellar) radiation. However, if there is a Galactic blackbody component, the correction procedure will not get rid of it. Therefore, what we observe may well have a blackbody component with a Galactic origin. In which case, one may wonder if the observed small scale fluctuations are indicative of turbulent patterns in our Galaxy rather than being the signature of galaxy formation in some early epoch.

The picture we have proposed for our Galaxy and its neighborhood could very well apply to other galaxies and thus we may see local microwave radiation fields around them. This may explain why we may still see the S-Z effect at large redshifts. We will return to this issue in the final discussion.

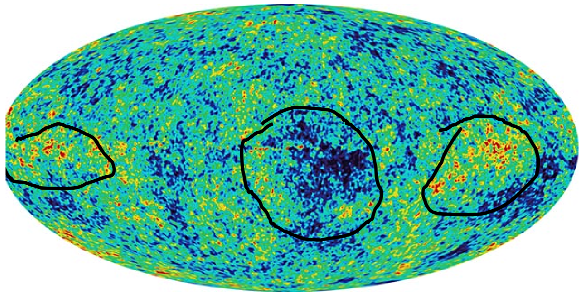

Fig. 1 Could the microwave features have originated in our own Galaxy? This image is from *WMAP*. On the original image of the sky issued by the NASA/*WMAP* group (see references), the authors indicated three remarkable regions dominated, unlike the rest of the map, by dark blue or red colors, signifying a peculiar behavior. They are located in the Milky Way. They defy any power-type analysis, in view of their large size and small number.

We end with a piece of evidence that may prove potentially hard to explain. This is related to solar motion measured relative to the rest frame of the MBR. The numerical values obtained by various sources may be summarized as follows:

(1) *COBE* data (1996): Solar apex: $l = 264°$ and $b = 48°$ with velocity towards the apex (estimated by us from the quoted data $\Delta T = 3.35$ mK and Wien's law) = 364 km s^{-1}.
(2) Landolt-Bornstein compilation (Landolt & Börnstein 1965): Solar apex with respect to galactic stars (the standard solar motion): $l = 56°$ and $b = 22.8°$ with velocity towards apex = 20 km s^{-1}.
(3) Velocity relative to the nearby extragalactic universe, as derived from Galactic rotation: Velocity at the Sun's location = 225 km s^{-1}.
(4) Apex of the Galaxy's motion relative to the extragalactic universe: this has been difficult to estimate but the order of magnitude value of the motion is expected to be around 100–200 km s^{-1}, as measured relative to the Local Group of galaxies.

From these figures, it is difficult to reconcile in an unambiguous way the *COBE* measurements with all that we know about the solar motion as summarized above. However, the existence of any solar motion relative to the MBR is disturbing for the RR-framework.

5 DISCUSSION

Our interpretation may be objected to on the grounds that it does not correctly take into account the S-Z effect, as applied to the photons from the MBR. This objection is not correct. The S-Z effect is in essence an inverse Compton effect linked with the interaction between incident photons and local electrons. The S-Z effect demonstrates that the MBR existed as far back in time as the typical redshifts ≥ 2 for clusters of galaxies. How does the apparently local origin of MBR account for this effect? To answer this question, we first note that a typical cluster containing several hundred galaxies will have starlight generated in similar amounts as in the nearby Virgo cluster of galaxies. There is nothing special about the thermalizing mechanism described here at it relates to our cluster, and it will be expected to operate in every cluster. In the standard picture, the background radiation present in a typical cluster of redshift z would have a thermal spectrum with temperature $T = 2.7(1 + z)$. Accordingly one could make a calculation of how much of this radiation is depleted in the millimeter region and enhanced in the high energy (typically X-ray) region by Compton scattering. The definitive ambient temperature makes this calculation relatively simple. In our model, we can likewise proceed so far as the calculation of Compton depletion and enhancement are concerned. However, the assumed thermal spectrum will have a temperature depending on the stellar background in the cluster. In short, we do not and cannot have a unique epoch dependent temperature on which to carry out such a calculation. Recent studies by *PLANCK* (Planck Collaboration et al. 2011a,b) have considerably enhanced the database of objects that exhibit the S-Z effect so as to enable us to propose a test to distinguish between the standard model and our model. First, we expect a larger variation in the magnitude of the effect, because the temperature of the background radiation varies from cluster to cluster even at the same epoch. Secondly, if we have optical details about the cluster, it may be possible to include that information to work out the X-ray enhancement. Then one may tabulate and plot the X-ray enhancement against the optical luminosity of the cluster. Provided such data are available in an unambiguous form, the S-Z effect holds out the possibility of distinguishing between this model and the standard model.

6 CONCLUSIONS

We would like to point out that the estimate of a stellar contribution to the MBR made here is based on the extensive HIPPARCOS database, used in its totality. Thus it leads to a considerably greater accuracy than the Eddington (1926) *rough* estimate, which used 2000 stars of magnitude 1 located at 10 pc to approximate the desired stellar contribution. Actually, Eddington only computed the temperature of the incoming Galactic radiation; he did not estimate or even consider the temperature of the dust, which can only be computed by taking into account, as we do, the distribution of light sources on the sky. Moreover, we also have the advantage of the *COBE* spectrum of the MBR for a comparison with the thermalized stellar background. Thus our work is based on direct observational evidence. For this reason the excellent agreement ($\approx$ 3% difference) found between the MBR temperature and that of the thermalized stellar background needs to be taken seriously. Another suggestive argument that favors thermalization is that the solar system seems to be entering a dense spiral arm of the Galaxy (McCrea 1975).

To summarize, we conclude that the RR interpretation deserves further consideration since *prima facie* it is able to provide a very accurate estimate of the observed MBR temperature, viz., 2.81 K in place of 2.726 K. The accuracy of these data is however not good enough to rule out a cosmological contribution, albeit as a minor component in the MBR. The validity of the RR paradigm, however, would imply considerably revising the standard model with potentially profound implications for cosmology.

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Appendix A: DETAILED COMPUTATION OF THE RADIATIVE FLUX RECEIVED AT EARTH

A.1. Introduction

The flux F received at the Earth is defined by

$$F = \sum_i F_i, \quad F_i = \int_\lambda F_{i,\lambda}(\lambda)\, d\lambda\,, \tag{A.1}$$

where the summation is made over all the sources of radiation, with each producing a bolometric flux F_i; each bolometric flux is the integral of the flux density $F_{i,\lambda}$ over all frequencies (or wavelengths).

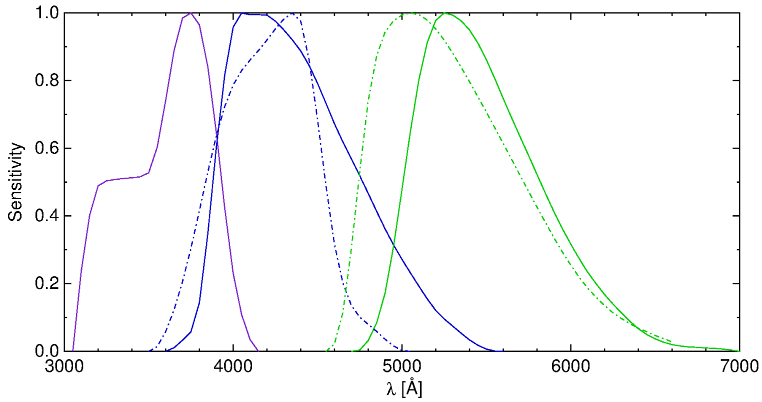

Fig. A.1 Sensitivity curves for the Johnson UBV (*solid lines*) and the Tycho $B_{\mathrm{T}}V_{\mathrm{T}}$ filters (*dotted lines*) *(from Maiz-Apellaniz).*

The computation of F was made with two different methods: the first method used the standard bolometric correction (Sect. A.2), and the second one used direct flux computations (Sect. A.3). Both methods rely on the usage of all-sky photometric surveys. Here, we use the Tycho-2 catalogue in the optical and the 2MASS in the near-IR.

A.1.1. The Tycho-2 catalogue

The Tycho-2 catalogue (Høg et al. 2000) resulting from the *Hipparcos* mission contains positions, proper motions and two-color photometric data for the 2.5 million brightest stars in the visible band. The satellite scanned the whole sky, and the result is a bias-free catalogue containing all the sources detected. The result is therefore especially appropriate for statistical applications.

The passbands used by the Tycho project, V_{T} and B_{T}, differ slightly from the Johnson BV standard colors (see Fig. A.1, adapted from Maíz Apellániz 2006): the central wavelengths (in Angstroms) of the Tycho system are 4192 and 5232 compared to 4380 and 5470 for the Johnson system (Fiorucci & Munari 2003). As a consequence, the color index $B_{\mathrm{T}} - V_{\mathrm{T}}$ differs slightly from the Johnson index $B - V$, with the average relation being $(B - V) = 0.850(B_{\mathrm{T}} - V_{\mathrm{T}})$ (Hipparcos, ESA 1997).

A.1.2. IR surveys

The fraction of light received in the red- and IR part of the spectrum can be computed from the 2MASS point source catalog (Cutri et al. 2003), which contains about 500 million point sources detected in the near-IR bands J (1.24 μm), H (1.65 μm) and K_s (2.17 μm).

A.1.3. The ASCC-2.5 catalog

Kharchenko (2001) combined the Tycho-2 catalogue with other ground-based astrometric catalogs, and also the 2MASS catalog. The result is a catalog of 2 501 313 stars, with accurate astrometry (positions, proper motions) and photometry in B and V (reduced to the Johnson system) plus the near-IR photometry from the 2MASS. However, it should be noticed that only a small fraction of the IR flux is received from optically bright stars – the ASCC-2.5 catalog is therefore not adopted for estimation of the flux received in the IR part of the spectrum.

Table A.1 Characteristics of the Filters and Their Zero-magnitude Fluxes

λ_0 (μm)	FWHM (μm)	Band	F_0 (Jy)	Remarks
0.419	0.067	B_{T}	3943	Tycho
0.438	0.093	B	4063	Johnson
0.523	0.095	V_{T}	3761	Tycho
0.547	0.084	V	3636	Johnson
0.610	0.063	r	3300	UCAC3
1.24	0.15	J	1594	2MASS
1.65	0.24	H	1024	2MASS
2.16	0.25	K_s	667	2MASS

A.1.4. Other all-sky surveys

The deepest all-sky surveys in the optical are still represented by the photographic surveys like POSS — but the photographic calibrations are generally not reliable, with the brighter part being absent. However, the UCAC3 all-sky survey (Zacharias et al. 2010) reports relatively accurate photometry in a band covering the wavelengths 579–642 nm, i.e. the orange-yellow part of the optical spectrum. The brighter stars ($\lesssim 4$) are absent from this survey; these were manually added.

A.2. Estimation with Bolometric Corrections

In a first step, we have used the V_{T} magnitudes of the Tycho-2 catalogue, and corrected them using a standard bolometric correction, given as a function of the spectral type. The stars from the brightest down to magnitude 2.5 (i.e. from Sirius ($V_{\mathrm{T}} = -1.088$) and Canopus ($V_{\mathrm{T}} = -0.608$) etc. to z Centauri ($V_{\mathrm{T}} = 2.497$), i.e. 142 stars altogether) were individually considered. For less bright stars, we have used bins of V_{T} magnitudes covering intervals of 0.25 mag down to $V_{\mathrm{T}} = 15$; to apply the bolometric correction, we have used the average value of the B_{T} magnitude for each bin. We have also considered the 15 brightest galaxies, from LMC ($m = 0.86$) down to NGC 4736 ($m = 8.91$), and applied a solar-like bolometric correction to the data. The examination of the data has demonstrated that stars less bright than $V_{\mathrm{T}} = 15$ do not contribute to the total flux received at the Earth. Our result is

$$F = 1.782\,10^{-2}\,\mathrm{erg\,cm^{-2}\,s^{-1}}. \tag{A.2}$$

A.3. Direct Estimation of the Flux

Here we try to directly estimate the flux of Eq.(1) from large all-sky surveys. The total flux of Eq.(1) can be derived directly from the observations in various filters, if the observations can be converted into actual fluxes. For this computation, we need to know, for each filter:

(1) its coverage along the electromagnetic spectrum. Here we assume this coverage can be reduced to a central wavelength λ_0 and a bandwidth W;
(2) the flux-magnitude relation, to convert the observed magnitudes (conventionally expressed in the Vega system) into actual fluxes. This relation follows the definition of the monochromatic magnitude $m_\lambda = -2.5\log(F_\lambda/F_{0,\lambda})$, where $F_{0,\lambda}$ represents the flux density of a zero-magnitude star.

The parameters adopted here are summarized in Table A.1 where the central wavelengths and their FWHMs are from the ADPS database (Fiorucci & Munari 2003), and the zero-magnitude factors are from the NStED[1] database, except for the UCAC3 where the value of 3300 was assumed

[1] NASA/IPAC/NExScI Star and Exoplanet Database, see *http://nsted.ipac.caltech.edu/NStED/docs/parhelp/Photometry.html*

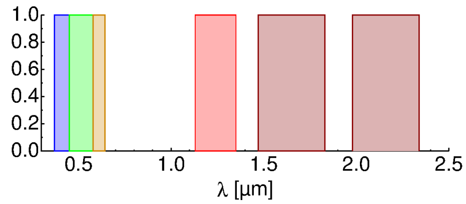

Fig. A.2 Illustration of the coverage of the electromagnetic spectrum used by the all-sky survey (bands $B_{\mathrm{T}} V_{\mathrm{T}} r J H K_s$).

Table A.2 Resulting figures for the total flux (in $\mu\mathrm{W\ m}^{-2}$) received in the bands summarized in Table A.1; values in italics are interpolations or extrapolations.

Band	Observed ($\mu\mathrm{W\ m}^{-2}$)	Completeness ($\mu\mathrm{W\ m}^{-2}$)	Faint end ($\mu\mathrm{W\ m}^{-2}$)	Total
F(B)	1.016	($m_B \leq 12$)	+0.479	1.495
F(V)	1.481	($m_V \leq 12$)	+0.654	2.135
F(r)	1.015	($m_r \leq 15$)	+0.275	1.390
F(J)	2.011	($m_J \leq 15$)	+0.412	2.510
F(H)	1.444	($m_H \leq 14$)	+0.275	1.719
F(K)	1.299	($m_K \leq 13$)	+0.259	1.558
gap	*4.412*	($m \leq 15$)	*+0.688*	5.010

from a comparison with similar filters. The relation between the bandwidth W and the FWHM is assumed to be $W = \sqrt{\frac{3}{2\ln 2}} \simeq 1.47$ FWHM, which stands for a Gaussian filter. The resulting coverage of the electromagnetic spectrum by the six bands is further illustrated in Figure A.2.

The observed fluxes in the B, V, r, J, H and K bands are illustrated in Figure A.3, which shows the variation of the flux density in each of the six bands as a function of magnitude. The behavior of the UCAC3 flux density in the range 7–9 mag is likely due to difficulty involved in the calibration of brighter stars.

Using the filter characteristics of Table A.1, the observed fluxes can be computed in each of the six bands. The results are listed in the "Observed" column of Table A.2 (non-italicized values), where the limits of completeness in each band are also specified. The limits in the completeness of the Tycho optical bands may be estimated with the photographic surveys, at least in the range 13–18 mag.

Figure A.4 shows the trends of the photographic blue and red magnitudes from the USNO-A2.0 catalog (Monet et al. 1998) which go beyond the limits of the Tycho-2 catalogue, where the decline can be estimated to be $d \ln N/dm \simeq -0.18$, *i.e.* an additional flux of the order of 5.5, the flux corresponding to the higher 1-mag bin. The final estimation of the fluxes in each filter are given in the right-hand column of Table A.2.

The gap between r and J bands was estimated from an interpolation between the V and J bands for the bright part ($m \leq 12$), and from an interpolation between the r and J bands for the fainter objects; the results of this estimation are given in the bottom line of Table A.2.

The remaining overlaps and small gaps in the coverage of the wavelength range 364 nm (Balmer jump) to 2.5 μm can finally be estimated with the linear approximation

$$\begin{aligned} F(0.364 - 2.5\ \mu\mathrm{m}) \;=\; & F(B_{\mathrm{T}}) + 0.908F(V_{\mathrm{T}}) + 0.782F(r) \\ & +1.216F(J) + 1.477F(H) \\ & +1.287F(K) + F(\mathrm{gap})\,, \end{aligned} \tag{A.3}$$

which finally gives the value $F = 17.1\ \mu\mathrm{W\ m}^{-2}$.

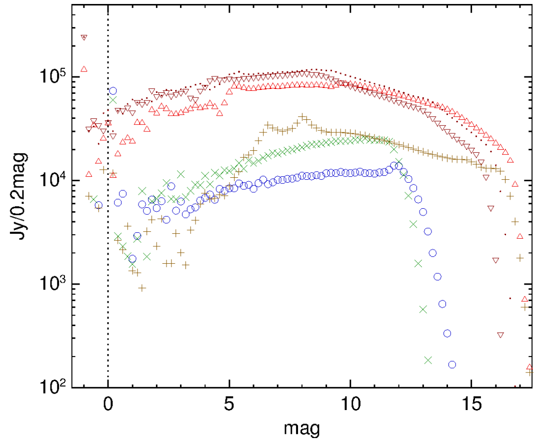

Fig. A.3 All-sky flux densities from all-sky surveys as a function of magnitude in bands B (*circles*), V (*crosses*), r (*pluses*), J (*triangles*), H (*dots*) and K (*inverted triangles*).

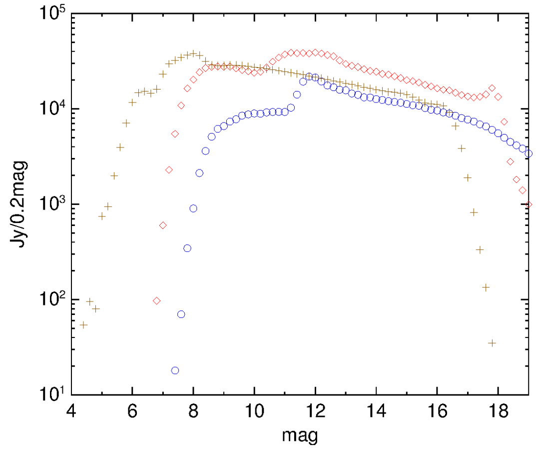

Fig. A.4 All-sky flux densities from the all-sky photographic survey USNO-A2 in B (*circles*) and R (*diamonds*); the pluses represent the UCAC3 magnitudes, as in Fig. A.3.

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